Investigating mechanisms of feature-based visual selection: Evidence from analyses of inter-trial, developmental, and affective modulations

Dissertation

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Introduction

Our perceptual environment abounds with information, only part of which can be processed: the human information processing capacity is restricted to handle a certain amount of load at any given time.
As an example, finding one's way around London's Kings Cross station, one of the biggest train, bus and underground stations in Britain, would be an impossible endeavour in case all the available information would be processed. A multitude of signposts informing about exits, train directions, train platforms, bus stops, ticket machines and timetables are wildly mixed with warning panels about how to keep cool in the heat, minding the gap and walking on the left while considering security; simultaneously, innumerable commercials and animated pictures are displayed to inform you about the latest must-haves. The above only refers to visual sensations; additionally, noises from trains and loudspeaker announcements about trains running late or being cancelled can be heard at different volumes. Smells from the food stands, perfumery shops or the burned iron from train brakes tickle the nose. On top of this, huge crowds of people constantly cross one's way and collisions need to be avoided.
The human brain, or the human information processing system, has to constantly make sense of this multitude of information. One of the key abilities in doing so is to select and, respectively, de-select information dependent on its relevance for the current behaviour and thinking. The cognitive mechanisms underlying information selection are referred to as 'selective attention' or 'attentional processes'.

Colin Cherry (1953) illustrated the selectivity of selective attention by means of the 'cocktail party' phenomenon – a well known situation everybody has experienced and understands. Imagine you are in a crowded place like at a cocktail party where you are talking to a couple of people in a little group. Although other people are talking and laughing next to you, glasses are clinking and there might even be some music playing, you are perfectly able to follow the ongoing discussion of your group. Physically, all the sensory information is processed and perceived (the sound waves are reaching the ear, pass malleus, incus, stapes and the cochlea and follow the auditory pathway until they reach the primary auditory cortex), but since it is not attended, no meaning is extracted from it, it is nothing but unimportant 'background noise' which is effectively ignored. However, if somebody in the room says your name, you probably shift your attention away from the discussion in your group in order to hear what people in that other group might be saying about you.

With the above described examples it becomes clear that attention can be conceived of as a limited resource which cannot be assigned to all available sensory information of the environment, and that attention is guided by our goals, motives and intentions to the currently relevant information. It is

therefore of great importance to understand the mechanisms underlying selective attention, particularly so, because almost all current theories of attention claim that only attended information has access to levels of conscious processing.

In the present PhD thesis I will discuss *when*, i.e., by what processing mechanisms, early or late, selection is achieved (section 1) and *what* type of information selection is based on (section 2). The most important methods used to measure underlying cognitive processing mechanisms of visual selection shall be reported as well as a selection of relevant results and their theoretical embedding (section 3). In the empirical parts of this thesis my own empirical studies and findings will be presented. The empirical part consists of four sections, the first of which is dedicated to the identification of the locus of selection (section 4), the second to the modulability of pre-attentive and post-selective (attentional) processes (section 5) and the third and the fourth report two innovative accounts investigating, respectively, the development of the mechanisms of selective processing (section 6) and the modulation of attentional selection mechanisms by the observer's affect state (section 7).

1. Classic studies on auditory and visual attention

The early classic studies of auditory and visual attention dealt with the question when in the processing stream between stimulus input and response output, to be exact, at which component process (stimulus → sensory/perceptual processing → linking/cognitive processes → motor/response preparation processes → response execution) selection is taking place. Two early accounts resulted from these studies claiming that selection is either located at the perceptual or at the action level. Both accounts are briefly discussed in the following sections.

1.1 Selection for perception

Broadbent's (1958) 'Filter Theory'

Based on three relevant findings Broadbent developed the Filter Theory: First, Cherry's (1953) investigation of attentional selectivity by means of the 'dichotic listening' paradigm, second, Broadbent's (1954) findings related to the 'split span' paradigm, and, third, Welford's (1952) description of the 'psychological refractory period'.

After having described the ability to follow one discussion and to ignore other ones at the same time, Cherry (1953, 'cocktail party' phenomenon) took the cocktail party to the laboratory by creating an experimental procedure referred to as the 'dichotic listening' paradigm. Via headphones, he presented participants with two independent messages, one going to the left and one to the right ear. Participants were asked to attend ('shadow') one of the inputs and to repeat it aloud. Interestingly, participants were hardly able to recall any information of the non-attended input. Participants had no memory of any semantic information; for example they did not notice if the language of the speaker changed from English to Czech pronounced like English or from meaningful to meaningless. However, they realised a disturbing tone (a 'beep') or the change of the speaker's voice from male to female.

In dichotic listening, the information that is to be ignored seems to be blocked early on in the processing stream, at a stage before information is represented semantically. Broadbent (1954) applied the split-span paradigm to test participant's ability to report semantic information in a setting which required what is referred to as divided attention. He presented series of pairs of digits simultaneously to the participant's left and right ears (for example 6-5, 9-4, 3-7 with the first number presented to the left, and the second one to the right ear). Participants, when asked to report the digits, grouped the numbers by physical input channel (6-9-3, 5-4-7) rather than by temporal order. Broadbent concluded that if participants have to extract meaning from different sources of information between which they have to switch, like the two ears, they try to reduce switching time costs by storing the information in

a short-term buffer from where it is retrieved for report. Thereby the physical properties of the information (source of information processing; i.e., ear) serve as a cue to organize sensory input.
The third relevant finding came from a study by Welford (1952), who showed that if participants were instructed to respond by manual button press to two visual stimuli presented in sequence, detection performance (as measured by simple reaction time, RT) to the second stimulus depended on the time that elapsed between the presentation onset of the two stimuli ('stimulus onset asynchrony', SOA). The shorter the SOA the larger were the RT costs to the second stimulus. Welford interpreted this inability to process two stimuli simultaneously in terms of a 'psychological refractory period' (PSP) reflecting a processing 'bottleneck' in which the processing of one stimulus must be finished before another stimulus can be processed. The fact that two stimuli presented in immediate sequence are processed serially can be seen as evidence for a central resource limitation of the information processing system.

Integrating these results Broadbent (1958) developed a first account on selective processing: 'Filter Theory' (see Figure 1a).
Two temporally simultaneously presented stimuli (or messages) get access to a sensory (short-term) buffer in parallel, but only one of them, based on its physical properties (e.g., ear), passes a selective filter. The other one remains stored in the buffer for a short period of time for potential later access. The filter is required to protect the serial capacity-limited processing system beyond the limited capacity channel ('single channel hypothesis', Welford, 1952) from overload. Only the information that passes the filter is exhaustively (semantically) processed by the system and is stored in long-term memory. Taken together, Filter Theory assumes that information is selected on the basis of physical stimulus properties at an early stage of processing and that due to a capacity-limited serial central processor sensory information is processed in an 'all-or-nothing' fashion.

Treisman's (1964) 'Attenuation Theory'
Following publication of Broadbent's (1958) Filter Theory, a number of studies investigating the question of whether or how much information presented to the unattended channel was processed at all, the strong claims of Filter Theory were found not to be tenable. In contrast to the assumption of processing being all-or-nothing in nature, Moray (1959) found break-through of non-attended 'meaning' through the filter: One third of his participants detected their own name in non-attended speech (see also the 'cocktail party' phenomenon, Cherry, 1953).
Lackner and Garrett (1972) showed the interpretation of ambiguous words in an attended message to be affected by the meaning of words presented in the non-attended message. Lewis (1970) demonstrated modulations of reaction times to shadowed words in a dichotic setting by simultaneously presenting either a synonym or an antonym of the words in the non-attended channel. Results show

that RTs to the shadowed word were decreased or increased, respectively, relative to the base RT ('Lewis effect').
Treisman (1960) alternated the ear site of the to be shadowed and the to be ignored message during the task and found some words of the message, now presented at the non-attended ear site to be processed and recalled. In another experiment (Treisman, 1964) she presented the same message to the attended and the non-attended ear. The message in the non-attended ear was processed, even when it was shifted in time, when two different languages or two different speakers were used.
Several other authors replicated semantic processing of non-attended material until a certain stage of processing (e.g., Gray & Wedderburn, 1960; Von Wright, Anderson & Stenman, 1975). Furthermore Underwood (1977) showed information processing in the non-attended channel to be subject to practice and training.

Treisman (1964) employed these results as the basis for a revision of Broadbent's (1958) Filter Theory which is referred to as 'Attenuation Theory' (Figure 1b). Treisman claimed that information filtering must not be in an all-or-nothing fashion, rather non-attended information is transmitted and processed in an attenuated, that is, a 'more-or-less' fashion. In detail, according to Attenuation Theory, a limited capacity processing channel is supposed to protect the cognitive system from overload. The perceptual input (encoded in parallel) is therefore filtered selectively. But rather than either being able to pass the filter (attended channel) or being stored in a short-term sensory buffer (non-attended channel), the non-attended information passes the processing bottleneck in an attenuated (weakened) fashion. Again, only the information that passes the filter (either through non-attenuated or attenuated channels) is then processed further and gets access to long-term memory. In summary, Attenuation Theory still assumes the existence of a relatively early sensory filter, although its locus in the processing pathway is subject to some flexibility. The functional architecture of AT is able to explain why, for example, a person's own name is perceived, although it is part of a non-attended stream of information. The activation threshold for the unit representing a person's own name is very low (or the resting activation of the name unit is very high) and its threshold is exceeded even when the name is perceived in an attenuated, i.e., non-attended channel (although it was shown that recognition is highly depended on the currently available processing capacity, which, in turn, would explain why not in all cases a person's own name is perceived).

1.2 Selection for action

In contrast to Broadbent (1958) and Treisman (1964), who argued in favour of an early (or relatively early) perceptual locus of selection, a radically different account claims that selection takes place late, at the response-related end of the processing stream.

Deutsch and Deutsch's (1963)' late selection' model

In their late selection model Deutsch and Deutsch (1963) advocated an account that was radically different compared to the early selection theories (Figure 1c). From their point of view, selection takes place at the level of the output, i.e., the response, component of the information processing system. This means that all incoming information, whether it is 'attended' or not, is automatically and exhaustively analysed. Subsequently only stimuli that are highly relevant for the current behaviour are processed further, for example for the programming of motor responses or to generate memory traces. Late, response-based selection requires a highly efficient weighting process that is able to rank all the incoming information dependent on its current relevance. Given a limited amount of time the required multiple comparisons cannot be achieved by serial processing (and in one single processing channel); rather, input analysis must be parallel in nature. Consequently according the Deutsch and Deutsch's account a filter selecting information based on physical properties is no longer required. Deutsch and Deutsch used the following analogy to explain the mechanisms of parallel comparison: The tallest pupil of a class can simply be identified by lowering a yardstick over the whole class. The pupil whose head touches the yardstick first is the tallest. In other words, with an appropriate strategy time-consuming multiple comparisons can be eliminated.

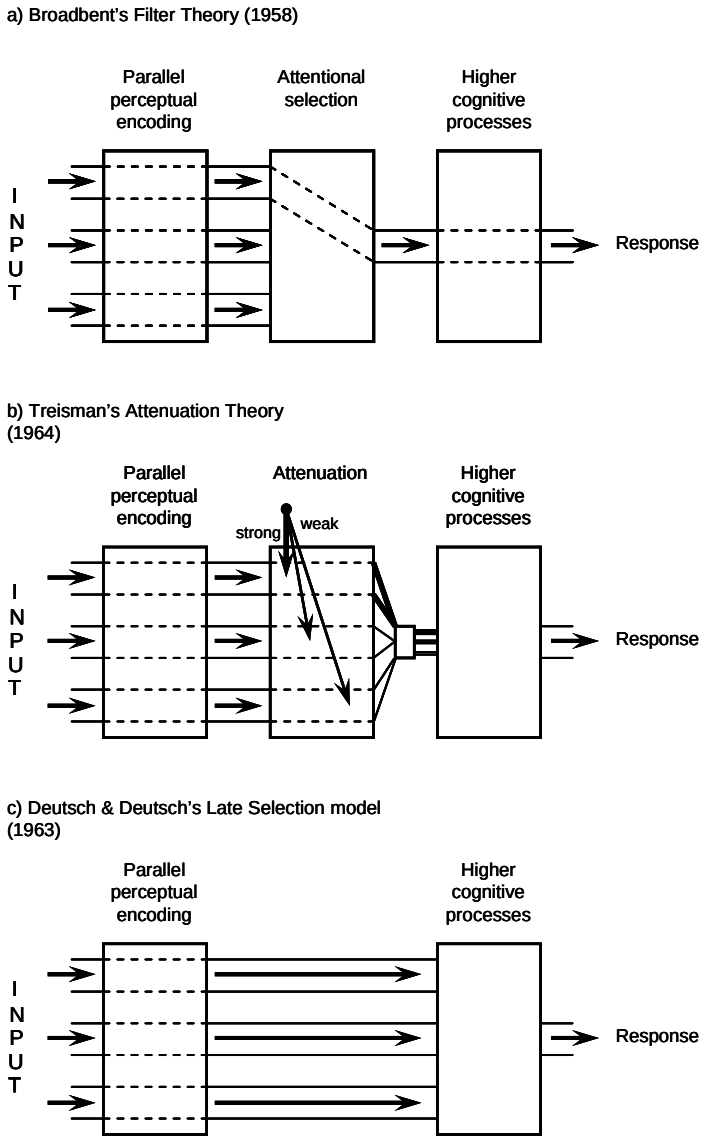

Figure 1. Schematic illustration of the early selection theories of Broadbent (filter theory, 1958; panel a) and Treisman (attenuation theory, 1964; panel b) and Deutsch and Deutsch's late selection account (1963; panel c).

1.3. Alternative accounts

Until today, the locus of selection is debated. Evidence both in favour of early and late selection accounts has been reported – and one of the objectives of the present thesis is to contribute to resolving the debate. An alternative approach was taken by Johnston and Heinz (1979) and Lavie (1995). Both attempted to resolve the theoretical dichotomy by proposing a flexible filter mechanism the operation of which is mainly determined by task difficulty. By varying task difficulty, Johnston and Heinz were able to modulate the magnitude of the Lewis effect (Lewis, 1970) and to systematically modulate the processing depth of the non-attended words. Johnston et al. therefore concluded that as the demand for processing capacity increases with an increase in processing stages

involved before selection, selection can be assumed to take place as early as task demands allow in order to minimize capacity requirements.

Lavie (1995) assumed that perceptual load plays the key role in determining the locus of filtering. By means of the response competition paradigm (Eriksen & Eriksen, 1974), in which a letter of interest is presented amongst irrelevant flanking letters, Lavie showed that if task demands require a large amount of attentional processing (high perceptual load) – for example because the irrelevant letters looked very similar to the relevant letter – there was only enough capacity to process the relevant letter. The fact that there was less interference from irrelevant distractor letters was taken as evidence for an early locus of the filter. If task demands were low (low perceptual load) – for example because the relevant letter could be easily distinguished from the neighbouring letters – the irrelevant letters were (at least partially) processed. They produced relatively more interference providing evidence for a ‘late’ filter locus in low-load conditions. Several studies (e.g. Handy, Soltani & Mangun, 2001; Johnston & Wilson, 1980; Lavie & DeFockert, 2003; O'Connor, Fukui, Pinsk & Kastner, 2002; Schwartz, Veilleumier, Hutton, Maravita, Dolan & Driver, 2005) supported Johnston and Heinz’ and Lavie’s hypotheses; therefore, good evidence for a flexible location of selection that is dependent on task demands calls into question the assumption of a simple answer (early or late) to the issue of whether there is an early or late filter stage in the processing stream.

2. Mechanisms of visual information selection

In the present chapter, the information on which selection operates is discussed. Traditionally, three different types of information selection mechanisms propose that selection is either space-based (2.1), object-based (2.2), or feature-based (2.3).

2.1 Space-based selection

Two different experimental paradigms were used to investigate space-based attention: The ‘flanker paradigm’ (Eriksen & Eriksen, 1974) and the ‘spatial cueing paradigm’ (Posner, 1980). The basic assumption is that all the information available at one circumscribed location in the visual field is selected at once.

Eriksen and Eriksen’s (1974) flanker paradigm

Eriksen and Eriksen (1974) introduced an experimental paradigm that since has been known by the name of the ‘flanker paradigm’. Their participants were presented with letters from two different sets, and, dependent on which set the target letter belonged to, observers were instructed to depress a pre-defined button (choice reaction). As an example, participants pressed the right-hand button when the target letter was an H or a K, and the left-hand key if the target was a letter S or C. The target letter was presented at a central location and it was ‘flanked’ by distractor letters which were completely irrelevant for the task at hand. However, dependent on the distance between the central target letter and the (horizontally) peripheral flanker letter, the distractors were found to interact with the target. Eriksen and Eriksen (1974) examined the distance at which distractors started to impair task performance by testing interference at three distance levels of 0.06°, 0.5° and 1° of visual angle between the central target and the flanking distractor letters. Eriksen et al. (1974) found RTs to decrease with increasing distance and concluded that 1° of visual angle was the smallest diameter of an attentional spotlight defining the area in space within which information is processed with priority. If non-relevant items are presented at a distance of less than 1° of visual angle, the target cannot efficiently be singled out (individuated) anymore for further processing (Figure 2); rather, distractor items are processed and cause a RT cost because they activate the relevant response codes.

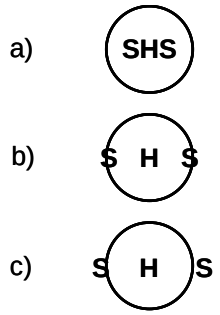

Figure 2. Schematic illustration of Eriksen and Eriksen's (1974) minimal attentional diameter. If distractors are presented closer to the target than 1° of visual angle (c), for example at 0.06° (a) or 0.5° of visual angle (b), distractors are co-processed and the target cannot efficiently be singled out.
Every object falling in the visual field with a diameter of 1° of visual angle is processed at once.

Posner et al.'s (1980) 'spatial-cueing paradigm'

In the influential paper titled 'Orienting of Attention' Posner (1980) suggested that attention, following the metaphor of a spotlight, is shifted between locations, whereby the information at any location is selected and made available for processing by higher cognitive functions. Executing shifts of the attention spotlight involves the three separate mechanisms of disengagement, movement and engagement. The disengagement mechanism 'detaches' the focus of attention from a given location (i.e., it terminates processing of information at that location), the movement mechanism directs attention to another spatial location and the engagement mechanism 'binds' attention to the new location. According to Posner's account, "attention can be likened to a spotlight that enhances the efficiency of the detection of events within its beam" (Posner, Snyder & Davidson, 1980, p. 172), the spotlight serves as a 'mental light', illuminating space to which attention is directed.

Posner's account is based on a series of findings of experiments in which a novel paradigm was used that he and his colleagues had introduced to the field: The 'spatial-cueing paradigm' (Posner et al., 1980). In the spatial cueing paradigm, observers are presented with a display consisting of a (central) fixation cross and two small peripheral squares to the left and right of fixation. The task of the observer is to indicate, as quickly as possible, the location (left or right) of a dot target appearing inside one of the two squares. Response is given by a left- or right-hand button press, referring to the respective target location. Before the target appears, a cue indicating the likely location (left- or right-hand square) of the target was presented at the location of the fixation cross. Cue validity was high; in 80% of the trials, the target appeared at the cued location (valid cue), consequently, the target appeared at the un-cued location in 20% of trials (invalid cue).
The question addressed by Posner et al. (1980) was whether the spotlight of attention is guided to a particular area of the visual field by a symbolic cue (the arrow pointing to one of the peripheral squares). In order to control for eye movements (i.e., the occurrence of eye movements instead of movement of the attentional spotlight), target exposure durations were very brief. Posner at al. (1980) found RT-benefits and -costs in, respectively, valid cue trials (the cue indicated the target location

correctly) and invalid cue trials (the cue indicated the target location incorrectly) compared to a neutral cue condition (a non-informative central cross).
Using the above experimental procedure, Posner et al. (1980) showed that attention can be shifted from one location to another by a voluntary, high-level process. Observers are able to follow the semantic instruction (arrow pointing to target location) in order to minimize reaction time. Due to the symbolic nature of the cue, the effect is referred to as an 'endogenous cueing effect' as the attention shift is generated internally, based on the observer's intention.

In a second experimental condition, Posner et al. distinguished two alternative mechanisms to control guidance of attention to a certain spatial location. Instead of indicating the target location with a central symbolic cue, a direct peripheral cue (a brief luminance increment of one of the peripheral squares) was used. Using direct peripheral cues, Posner et al. (1980) found cueing benefits and costs for valid and invalid cues similar to the ones found with symbolic cues. However, as an external cue was used, the effect is referred to as generated 'exogenously' and not necessarily subject to participants' intentions. Comparing the two cueing conditions, Posner et al. (1980) demonstrated that exogenous cues seem to attract attention in an automatic fashion and to override endogenous cues when both types of cue are presented concurrently in a trial. Whereas endogenous cues can be ignored (at least in the case of very low cue validity) exogenous cues cannot be ignored.

These results reflect the existence of two complementary mechanisms of attention allocation: A voluntary and controlled mechanism based on one's internal goals and a reflexive and relatively automatic mechanism based on external stimulation (Müller & Rabbitt, 1989).

Limitations of the spotlight metaphor

The spotlight metaphor has a number of serious limitations which cannot be overcome (see Cave and Bichot (1999), for a review). For example it remains unclear whether the spotlight, when shifted between locations, 'jumps' from one location to another in a digital, instantaneous fashion or whether it moves in an analogous, time-consuming fashion, attentionally illuminating all the way between the initial starting and final location in visual space.
Evidence for this latter possibility is found in Posner et al. (1980) who showed that after the presentation of a central cue performance benefited from a longer stimulus onset asynchrony (SOA) between cue and target onset, indicating that the spotlight needed some time to be shifted to the cued location (see also, Tsal, 1983).
On the other hand, Shulman, Remington and McLean (1979) found evidence for the latter hypothesis by obtaining equal reaction times to cued targets that were far away from fixation and un-cued targets that were presented near fixation. Shulman et al.'s result is at variance with the hypothesis that the attentional spotlight moves through space in an analogous fashion.

Another critical point is concerned with the issue of whether attentional resources are distributed homogenously within the spotlight, that is, whether the boundary of the spotlight is characterized by a sharp borderline or by a gradient. The 'gradient account of attention' for example claimed that the spatial distribution of attention follows a gradient; the effects of attention allocation decrease with increasing eccentricity from the centre of the attentional focus (Anderson, 1990; Downing, 1988; Downing & Pinker, 1985; Eriksen & Yeh, 1985; Hoffman & Nelson, 1981; LaBerge, 1983; LaBerge & Brown, 1989; Mangun & Hillyard, 1987, 1988; Shaw & Shaw, 1977).

Besides some other ambiguities (for example about whether the spotlight can be split into multiple spots with attention allocated to more than one single location at a time or concerning the shape of the selected area and whether the shape of the spotlight can be modified or not), a prominent discussion concerned the issues on whether the spotlight and therefore the selected area is of a constant size or whether the diameter of the attention focus is flexible. According to Eriksen and Eriksen (1974) and Posner (1980) the attentional spotlight and therefore the selected area is defined by minimum constant size (minimum diameter of the attention spotlight of 1° of visual angle). Other authors, by contrast, claimed that the width of focal attention is variable; they liken attention to a variable 'zoom lens' rather than a fixed-size spotlight, because the diameter of the selected location was empirically shown to depend on observer's volition or task demands (e.g., Eriksen & Murphy, 1987; Eriksen & St. James, 1986; Eriksen & Yeh, 1985; Jonides, 1983; LaBerge, 1983).

An important piece of evidence was provided by LaBerge (1983) who used a probe to assess the extent of the attentional spotlight. Participants were instructed to report the presence of a probe (the digit '7') as a secondary task in a dual-task paradigm. Participants were presented with five-letter words or non-words. The spread of attention was manipulated in two conditions. In the first condition participant's task was to categorise the central letter of the five-letter words or non-words; in the second condition, they had to categorize the entire string of letters a word or non-word. The assumption was that in the first condition the spotlight would be narrowed down to the central letter of the word, but that in the second condition the focus of attention would be spread over the whole word. The results were compatible with the hypothesis: RTs to the probe in the letter categorisation task were highly dependent on the position of the letter in the word where the probe was presented. RTs were substantially faster when the probe was presented at the central (the attended) letter position. At any other letter position RTs were substantially increased compared to the middle letter of the word. As expected, in the word categorisation task RTs to probes were independent of presentation location of the probe. This pattern of results suggests that the diameter of the attentional spotlight is not fixed; rather, it is variable in size and subject to modulation by task demands.

Eriksen and St. James (1986) came to the same conclusion by means of a spatial cueing paradigm in which stimuli were arranged in a circular fashion (one target letter amongst seven distractor letters located on an imaginary circle around fixation). Eriksen et al. varied the number of (contiguous) cued

locations from one to three and obtained cueing effects for targets that were presented at cued locations. More importantly, by increasing the number of cued locations an increase in RTs was obtained indicating additional co-processing of distracting neighbouring letters and an increase of the attentional focus over and above the pre-cued area.

Broadbent (1982) summarised these results by stating that we should "think of selectivity as like a searchlight, with the option of altering the focus. When it is unclear where the beam should go, it is kept wide. When something seems to be happening, or a cue indicates one location rather than another, the beam sharpens and moves to the point of maximum importance." (Broadbent, 1982; p. 271). Moreover, Lavie's findings suggested that the focus of attention may be yoked to the overall load or difficulty of a task (Lavie, 1995; Lavie & Tsal, 1994). In combination with the zoom lens metaphor one could conclude that a high cognitive load causes a narrowing of the attentional focus; irrelevant events are excluded from the spotlight and remain non-attended and non-processed. By contrast, a low perceptual load allows the spotlight to expand over additional, irrelevant, areas of the visual field. Thus in order to ensure proper target processing one should make sure that the overall perceptual load of the task is sufficiently high.
Concerning the spotlight metaphor and its theoretical extensions, Cave and Bichot (1999) concluded that "this metaphor has been useful over many years for generating experimental questions in attention research. However, theories and models of visual selection have reached such a level of complexity that debate now centres around more specific questions about the nature of attention" (Cave & Bichot, 1999, p. 204).

2.2 Object-based selection

Duncan (1984), in a highly influential paper, proposed that attentional capacity limitations are not due to attentional restrictions to a certain location, but to the fact that just one object at a certain location is processed at once. Only attention allocation to a specific object enables higher cognitive processing of the object attributes. In Posner et al.'s (1980) cueing paradigm the to-be-attended locations were marked with squares (objects) to which then attention was directed. Duncan tested the hypothesis of object-based selection by presenting observers with two superimposed objects for a short period of time. Participants were asked to judge one (single judgement) or two (dual judgement) object characteristics of either one or two objects. Each object was characterized by two independent attributes: Small versus large rectangles with a gap on either the left or right side and dashed or dotted lines either tilted to the left or right (Figure 3).

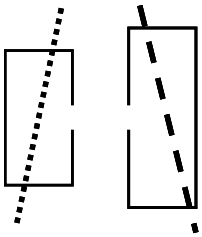

Figure 3. Duncan's (1984) superimposed objects. Each object was defined by two independent features: rectangles were either small or large and had a gap on either their left or right side and lines were either dashed or dotted and either right- or left-tilted.

Experimental results revealed that judgement accuracy for single and dual judgements of only one object was equal; however, accuracy dropped substantially when observers had to report two attributes of two objects compared to dual judgements on characteristics of only one object. This was the case although both objects were presented at the same location and extended less than 1° of visual angle. The finding is in accordance with Duncan's (1984) assumption that selection is directed to one object at a time rather than being spread over several objects at abstract locations in the visual field. Duncan's (1984) results were replicated several times since (e.g., Lavie & Driver, 1996; Vecera & Farah, 1994). Baylies and Driver (1993) used objects like those presented in Figure 4, and they showed that judgements on the location (below or above) of left relative to the right vertex were more accurate if both vertices were part of the same object (Figure 4, left panel) compared to when they were part of two different objects (Figure 4, right panel).

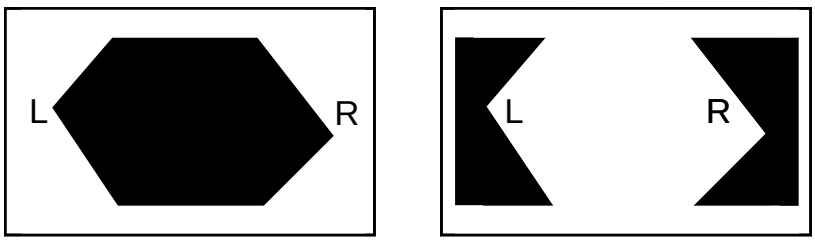

Figure 4. Baylies and Driver's (1993) experimental figures. Observer's task was to judge about the vertex positions (L, R) which belonged to either one (left panel) or two (right panel) object(s).

Applied to object-based theories of selection, such as Bundesen's Theory of Visual Attention (TVA; Bundesen, 1990, 1998) the basic assumption of these models is that the entire objects are selected and processed at a given time. According to TVA, all objects in the visual field compete for identification. In order to be identified, an object has to be categorised (object o belongs to the category c). Only when categorisation was successful, the object is encoded in the visual short term memory (vSTM) and can be compared to long-term memory representations for recognition.

Inhibition of return (IOR)

The finding that attention is directed to objects should not be taken as evidence that attention cannot be directed to locations. Both types of attention allocation are possible. First, it is very obvious that objects are characterized by spatial components: every object presented in a visual scene occupies a certain location. Second, there is empirical evidence from investigations of 'inhibition of return' (IOR; Maylor, 1985; Nakayama & Mackeben, 1989; Posner & Cohen, 1984), a phenomenon that was observed in a peripheral cueing experiment. If the target appeared with a delay of 300 ms or more after a valid cue, target detection was slowed down compared to when the SOA between cue and target was smaller than 300 ms. The usual effect of facilitation was reversed and had changed into an inhibitory effect. The phenomenon describes the fact that once attention is disengaged from a certain spatial location or object, it is harder to return attention to the same area or object for a given amount of time. IOR can be space- or object-based (Gibson & Egeth, 1994; Logan, 1996; Müller & von Mühlenen, 1996; Tipper & Weaver, 1998; Tipper, Weaver, Jerreat & Burak, 1994). Intuitively, in everyday vision as well as in experimental settings, IOR seems to be a powerful mechanism to prevent the visual system from 'revisiting' already investigated locations or objects that were found to be uninformative as to the current goals (Klein, 1988). However, in the laboratory the existence of IOR was not always confirmed (e.g., Horowitz & Wolfe, 1997; Wolfe & Pokorny, 1990).

2.3 Feature-based selection

According to feature-based accounts of visual selection, it is object characteristics – features – that underlie selection rather than whole objects or spatial locations. For example, object-based accounts are not able to explain why, when looking at a basket of many green and one single red apple, the red apple seems to literally 'pop out' of the basket. By means of feature-based selection, the experience of pop out can easily be described (as will be seen in chapter 3.3). It was shown that features of a limited set of feature categories or 'dimensions' such as colour, orientation, curvature, size and motion (for an overview of dimensions, see Wolfe, 1998) can be used to describe an unlimited number of objects. As an example, an apple can be described by its colour, shape and size (dimension), with the possible features red, green or yellow (colour) and small or big (size).

Prominent theories assuming feature- or dimension-based selection are the 'Feature Integration Theory' (FIT; Treisman, 1988; Treisman & Gelade, 1980; Treisman & Sato, 1990) and the 'Guided Search' model (GS; Wolfe, 1994; e.g. Cave & Wolfe, 1990). Due to the fact that some knowledge about the experimental paradigms employed to provide the empirical data bases underlying the theoretical accounts, both FIT and GS are described in the next chapter (section 3). Chapter 3 will be dedicated to the method of 'visual search', its results and theoretical interpretations.

3. Visual search: paradigm, results, theories

The visual search paradigm is known as a very powerful psychometric procedure for investigations into the processes underlying feature-based attentional selection. It is especially powerful due to the possibility to investigate a wide range of effects of selection by only minor variations design-wise. In the present chapter, the visual search task (3.1), the key findings of parallel and serial search mechanisms (3.2) and a selection of the most important theoretical models developed to account for these results (3.3) shall be discussed. In the concluding section (3.4), a special analysis technique, namely the analysis of inter-trial effects in searches across feature-dimensions as well as the corresponding theoretical background is discussed in detail.

3.1 The visual search task

In experiments using the visual search procedure, observers are presented with displays containing an array of non-target or 'distractor' items. Among these a particular target item may or may not be presented. In the situations of everyday life, one might for example be searching for a red apple in a basket of green apples. In the laboratory, in order to optimally control as many potentially interfering parameters as possible, often real world objects such as apples are replaced by simplified artificial items, defined by a limited number of features; consequently, observers might search for a (unique) red vertical bar among green vertical bars.
The total number of presented items is referred to as the 'set size' or 'display size'. The Observers' task is to decide whether or not a particular target is present in a given display or not. They are instructed, in terms of a two-alternative forced choice, to indicate their decision about the target's presence or absence as quickly and accurately as possible by pressing one out of two predefined response keys (manual response).
Search reaction times (RTs), defined as the time elapsed between display onset and key press, and the proportion of trials responded to correctly ('hits' in the case of target presence and 'correct rejections' in the case of target absence) and erroneously (false alarms and misses, i.e., present-responses in trials where no target was present and absent-responses in situations with a target present) are analysed as dependent variables. RTs as well as errors are analysed in order to exclude so called speed-accuracy-trade-offs (SATO). SATO is based on the possibility that some of the observers might be willing to respond as fast as possible on the expense of accuracy; any RT differences confounded with SATO can and must not be interpreted.

Search reaction time functions

The search rate, the time that is needed to process a display item and to decide whether it is the target (present-trial) or not (absent-trial) can be evaluated by means of the search reaction time function; the search reaction time function relates search RTs (plotted on the y-axis) and set size (n; plotted on the x-axis) in the linear function of $RT = a + bn$.

The y-intercept of the function reflects the base RT *a*. *a,* is a measure for the overall difficulty of the search task; the slope of the function *b* reflects the search rate (search time per item). The steeper the function, the longer it took observers to process one display item and to decide whether it corresponds to the target template or not (increased search rate). The higher is the search rate, the more time it takes to process a given display item.

In several search experiments substantially different search functions were observed (e.g. Treisman & Gelade, 1980). Based on this finding, two types of visual search were proposed. If search functions increase only little (if at all) with increasing set size (by convention: $b \leq 10$ ms/item) it is assumed that all the items in the display are searched simultaneously or in parallel.

On the other hand, if search functions increase linearly with increasing set size (by convention: $b > 10$ ms/item), it is assumed that display items are scanned successively (stepwise, one after the other) or serially.

3.2 Parallel and serial search

Treisman and Gelade (1980) differentiated two types of search accounting for the different search functions: ‘feature’ search and ‘feature conjunction’ search.

In feature search, the target differs from distractor items by a unique single feature within a particular dimension (e.g., colour: a red apple in a basket of green apples). Such ‘feature singletons’ seem to literally ‘pop out’ of the search display, even when they are presented within a large number of (homogeneous) distractor items. RTs in feature search are independent of set size and they produce flat (shallow) search reaction time functions. Therefore, one can conclude that feature singletons, i.e., odd items in a display, are detected by a process of parallel analysis of all display items.

In feature conjunction search, the target differs from distractor items in a unique conjunction of multiple features on at least two dimensions (e.g., colour and size: the unique red big apple in a basket of red small apples, green big apples, and green small apples). RTs in conjunction search conditions depend on display size; the more items are presented in a display, the steeper the search function increases with increasing set size. That is, a target defined by a feature conjunction is searched for by a serial process (Treisman & Gelade, 1980).

Whereas in feature search, due to the parallel nature of processing, the slopes of the search functions are equal in target-present and target-absent trials (Figure 5, top panel), in feature conjunction search

involving serial processing, target-absent search slopes were found to be twice as steep as target-present search slopes (Figure 5, bottom panel). In conjunction search, in a target-absent trial with display size *n*, *n* search steps are required in order to ensure that no target is present in the display. In other words, search is exhaustive because every item has to be checked for a possible match with the target template. In a (conjunction search) target-present trial with a set size *n*, search is terminated as soon as the target is found (self-terminating search). Statistically, this happens after $n/2+½$ search steps, because, on average, the target is found after half the display items have been processed. Consequently, there is a 2:1 ratio between the search function slopes for serial target-absent and target-present search trials; the slope for serial target-absent search is twice as steep as for serial target-present search (given constant duration for individual search steps and the assumption that each item is processed only once).

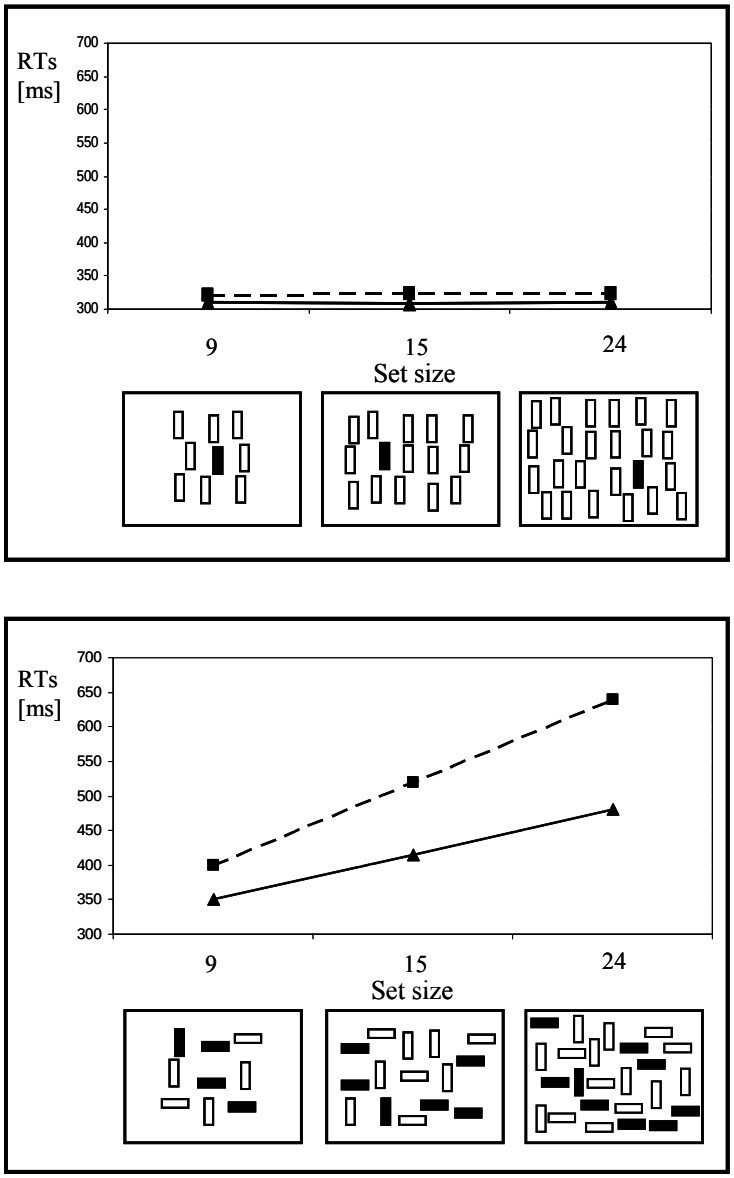

Figure 5. Schematic illustration of simple feature (top panel) and feature conjunction search (bottom panel) displays and according search functions. Considered a dichotomous distribution of search types, parallel searches reveal flat search functions independent of set size for target absent as well as present trials, whereas serial searches reveal steep search functions increasing linearly with increasing set sizes. Target absent functions are twice as steep as target present functions.

3.3 Theories of visual search

In order to explain the dichotomy between feature and feature conjunction searches, a number of different theoretical accounts were proposed. Among the most influential theoretical models of visual search and visual information processing are the 'Feature Integration Theory' (FIT; Treisman, 1988; Treisman & Gelade, 1980; Treisman & Sato, 1990) and the 'Guided Search' (GS) model (Cave & Wolfe, 1990; Wolfe, 1994; Wolfe, Cave & Franzel, 1989).

Both the FIT and GS models are characterised by an architecture involving two consecutive processing stages with the first stage generating input for the second stage. The basic assumption of all

feature-based models of selection is that every stimulus can be described by a combination of (a limited set of) basic features (see above 2.3) and that selection is based on visual features. On the first processing stage, features are extracted from the visual field in parallel and represented in spatio-topically organised feature maps (topographical feature representation) within the relevant dimension-based module. In detail, dimension-based feature maps contain representations generated by feature detectors signalling the presence of a particular feature at a particular location in the visual field. Features are conceptualized as variable instances of dimensional representations, that is, each feature (i.e. red, green, yellow) is represented in the specific dimensional module (i.e. colour module) between which (on the first processing stage) there is no interaction or crosstalk.

The Feature Integration Theory (FIT)

According to FIT (Treisman, 1988; Treisman & Gelade, 1980; Treisman & Sato, 1990), the feature- or, respectively, dimension-based representations signal the presence of particular features at particular locations in the display. Feature map units respond in an all-or-nothing fashion; at a given location on the feature map there is either a feature signal, or there is none.

The assumption that the available features of the visual scene are processed separately leads to the basic question of how these individually processed features are integrated (bound together) into a coherent object representation. The question addressing the integration of multiple representations is referred to as the 'binding problem'. According to FIT, features at a certain location in the visual field are bound together if focal attention is allocated to that location. Attention allocation is controlled by the master map of locations.

The functional role of focal attention is that of 'glue' that integrates the initially separately represented features into unitary object representations. According to the model, feature integration is achieved at the second stage of processing. Focal attention is directed to one location of the overall (master) map of locations and thereby features represented in separate feature maps are gated to higher level cognitive processes where features are represented in an integrated object-based fashion (object files). Stated differently, feature information is fed into temporary object files that maintain a temporary list of the object-describing features. Temporary object descriptions are matched with objects stored in long-term memory (LTM) and, if there is a match, an object is recognised (and categorized as target or non-target) (Figure 6).

The processes of the first, parallel, stage are thought to be automatic in nature, that is, they are independent of limited resources, and they are not subject to modulation by cognitive (i.e. attentional) processes. For these reasons, processes of the first stage of FIT are referred to as 'pre-attentive' processes. The second processing stage is assumed to work in a serial fashion, that is, a particular selection of the representation is given processing priority.

To summarize, efficient feature searches are primarily based on mechanisms of the first, parallel, stage of processing; attention allocation is not required in feature search tasks, because no feature integration is required. In other words, pre-attentive processes are sufficient to detect the presence of the target. In contrast, inefficient feature conjunction searches require the allocation of focal attention and feature binding for target identification.

The selection bottleneck, according to FIT, is in the limited capacity of the binding stage. In particular conditions in which conjunction search displays were presented for short exposure durations, illusory conjunctions were reported (Treisman & Schmidt, 1982). The term illusory conjunction refers to the fact that features of un-attended objects were bound together incorrectly (as an example, the form feature of object 1 is bound together with the colour feature of object 6), because there was not enough time to shift and allocate focal attention to all the display items. Only the allocation of focal attention to a particular display location allows for the correct integration of features.

However, a number of findings that were at variance with FIT were published. One such finding showed that there was a great variability of slopes of search functions; search slope variability is difficult to explain with the simple dichotomy of parallel pre-attentive feature and serial attention-based conjunctions search as claimed in FIT. Search experiments revealed search functions with slopes on a continuum between flat (feature search) and steep (conjunction search) irrespective of the task at hand; i.e., feature searches would produce increasing RT x set size functions while conjunction searches would produce search RT functions independent of set size (Cave & Wolfe, 1990, see also Wolfe, 1998, for an overview). The issue of search slope variability is addressed in an alternative to FIT, the GS model (Cave & Wolfe, 1990; Wolfe, 1994; Wolfe, Cave & Franzel, 1989).

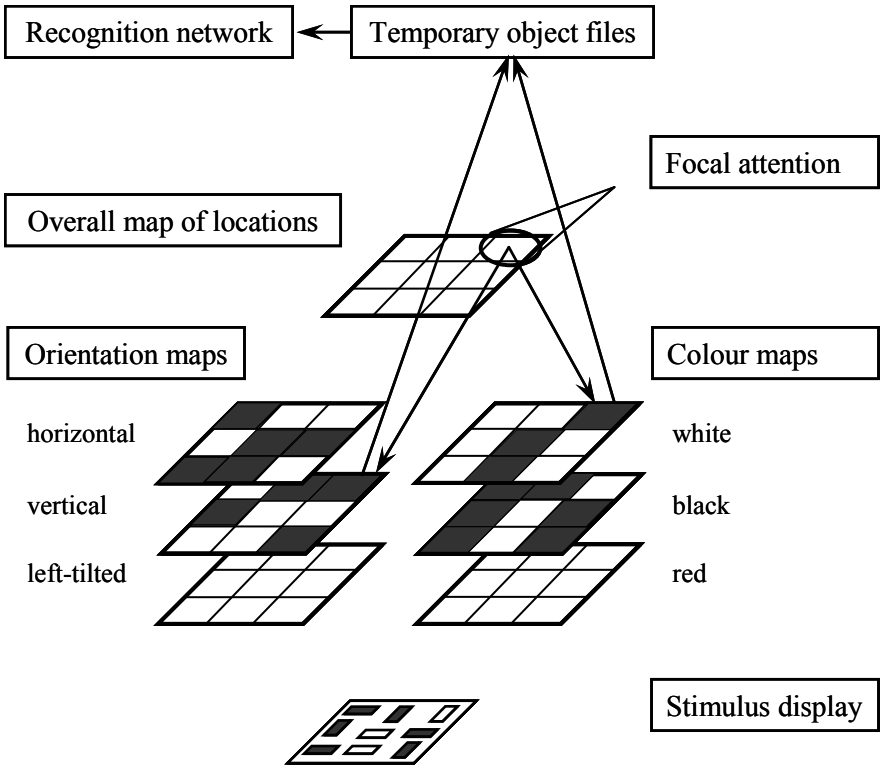

Figure 6. Functional architecture (according to Müller & Krummenacher, 2007) of the Feature Integration Theory (FIT; Treisman, 1988; Treisman & Gelade, 1980; Treisman & Sato, 1990).

The Guided Search (GS) model

In the framework of GS (and in contrast to FIT), the topographical dimension-based feature representations are the basis for the computation of 'saliency activities' signalling the presence of conspicuous features at particular locations in the display [1]. The higher the contrast between neighbouring items, i.e., the more dissimilar a display item is compared to the surrounding items, the higher is its dimension-based saliency activation [2].

[1] Koch and Ullman (1985) proposed the idea of saliency representations and distinguished between local dimension-specific saliency maps and a global map of integrated saliency at the end of pre-attentive mechanisms of selection. Itti and Koch (2000) used the saliency concept for the implementation of a computer-based algorithm which is comparable to the mechanisms that are thought to underlie pre-attentive selection in the primate visual system.

In the ensuing second processing stage of GS, the separate dimension-specific saliency activities are integrated (summed) onto a location-based 'priority map' (in earlier versions of GS the priority map was known as 'overall map of activations' or 'overall saliency map') on which focal attention operates. In contrast to FIT - in which the master map of locations only controls the allocation of spatial attention - in GS, the priority map does not receive any direct input from the feature representations; rather, the priority map integrates activation from dimension-specific saliency maps. After summation onto the priority map, focal attention is allocated first to the location containing the highest saliency activity (in a winner-takes-it-all fashion) and the features present at that particular location are gated to higher-order cognitive processes (of object recognition and/or response generation). The higher-order cognitive processes also take the decision as to whether the item at a given location is the target or not. If the currently scrutinized object corresponds to the target template a response is generated, if not, focal attention is directed to the location exhibiting the second highest peak of activation. The process is repeated until the target is found (self-terminating search) or all display items have been searched (exhaustive search).
It is important to note that the priority saliency signal does not carry any information as to the target's (feature or dimensional) identity; it merely codes salient locations of the visual scene.

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[2] The Attentional Engagement Theory (AET; Duncan and Humphreys, 1989, 1992) also uses similarity comparisons between display items to explain effects of selection. According to AET, the basic factors determining search performance are the (dis-)similarity between targets and non-targets and the (dis-)similarity between non-targets. The result of these comparisons in terms of slopes of the search RT function is reflected in a 'search surface'.(Figure i). If the target-to-non-target similarity is low (A), the search function is flat and performance is not affected by the similarity or dissimilarity of non-targets (A-C). Even with the maximum homogeneity between the non-targets (A) the slope of the search function increases with increasing target-to-non-target similarity (A-B). In general, as non-target heterogeneity (towards C) and target-to-non-target similarity (towards B) increase, the slope of the search function increases continually (maximal slope at D).

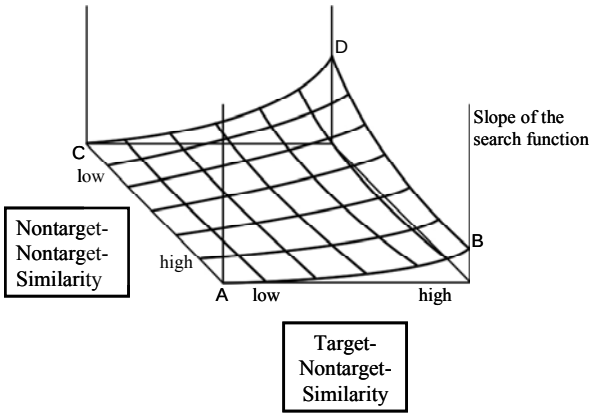


Figure i. Schematic illustration of the search surface based on target-distractor (dis-)similarities as proposed by the Attentional Engagement Theory (AET).

In contrast to FIT, in GS the first pre-attentive as well as the second attentional processing stage are involved both in feature and feature conjunction searches. In GS, the functional role of attention is to provide preferential access to higher-order processing for conspicuous visual information. This holds true for all feature information, simple features or feature conjunctions.

In order to explain some specific effects of search, GS involves not only a bottom-up component (as early versions of FIT) but also a possibility to top-down modulate guidance in visual search. In the case of a simple feature search bottom-up guidance on the basis of its priority saliency activations is completely sufficient for target detection (Figure 7, top panel). The saliency signal on the priority map for a feature singleton target is always the most prominent peak, because the target produces a strong contrast signal relative to the distractors. Attention is directly guided to the target's location first. In feature conjunction search, visual attention is guided by top-down processes in such a way that top-down connections excite units coding features that characterize the target [3]. That is, generation of the dimension-based saliency signals is directly influenced by top-down knowledge (Figure 7, bottom panel).

Attentional guidance depends on effects of similarity or dissimilarity between target and distractor items. Similarity can explain the findings of various search reaction times x set size slopes. The lower the contrast between the display items (for example in conjunction searches), the higher is the noise on the master map of activations (compare Figure 7 top and bottom panel), consequently, focal attention might be misled to some varying degree.

[3] In the first version of GS (Wolfe, Cave & Franzel, 1989) it was not clear, whether the top-down modulations are thought to be excitatory for target features or inhibitory for non-target features. In GS 2 (1994) Wolfe determined top-down processes to be excitatory in nature.

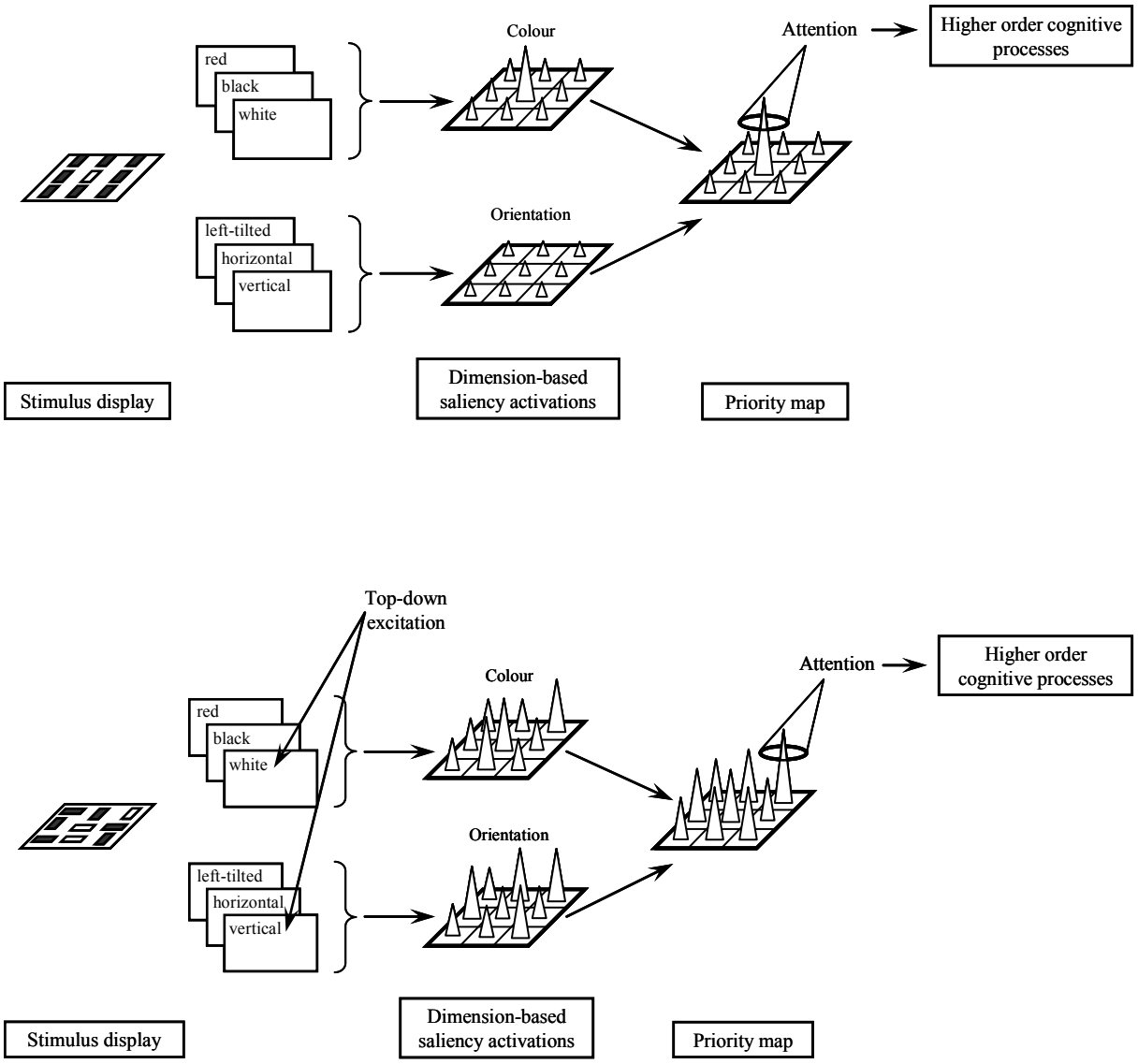


Figure 7. Functional architecture (according to Müller & Krummenacher, 2007) of the Guided Search model (GS; Cave & Wolfe, 1990; Wolfe, 1994; Wolfe, Cave & Franzel, 1989) in case of a simple feature (top panel) and a feature conjunction (bottom panel) search.

Discussion of FIT and GS

The saliency-based account implemented in GS seems to have gained the upper hand over FIT in recent research, mainly due to the fact that GS has a greater explanatory power for visual search performance. Besides the ability to account for the diversity in observed search function slopes, there are number of other phenomena that GS, in contrast to FIT, is able to explain.

As an example, original versions of FIT have difficulty explaining the detection of a feature singleton target, i.e., a target the definition of which is not known at the beginning of a given trial, or, stated differently, a target that is defined as an odd item in the display. According to GS, the simple mechanism of guiding attention (in a purely bottom-up fashion) to the spot with the highest activation on the priority map explains that and how the odd item pops out of the display. In the case of a feature

target, the spot with the highest activation corresponds (with high probability) to the location of the singleton. (Note that, in singleton feature displays with the target differing in at least one feature from a homogeneous set of distractors, there is no noise to disturb the feature contrast signal.)
For these reasons outlined above (as well as other reasons) in a revision of FIT (Treisman & Sato, 1990) a mechanism of top-down control was included. With the assistance of top-down control, features that are known to be irrelevant (because they do not define objects in a given trial) can be excluded from attentional scanning (in detail, all the green locations are inhibited when the target is known to be red, i.e., not green). The mechanism of top-down modulation in FIT is thought to be an inhibitory effect (in contrast to the excitatory top-down modulation implemented GS) that – following the concept of early de-selection of irrelevant information - reduces the effects of irrelevant information. In the case of top-down inhibition, the feature units do not signal presence of any stimulus at irrelevant locations and attention is not allocated to these locations. These top-down mechanisms, however, are operative only if the target-defining features are known. If so, a homogenous field of distractors can be inhibited and rejected in parallel (FIT). The only active location remaining is the target location. The target pops out and "calls attention" (Treisman, 1988, p. 205) to its location automatically (without requiring serial scanning).
Note also, that implicitly this mechanism has been assimilated by GS. With the modification of FIT, the locations are no longer coded in an all-or-nothing, but a graded fashion rather and the master map of locations is more similar to a saliency map.

Following the rationale of GS one can conclude that "[a]ssuming that processing within dimensions is equally fast, the appearance of a high-activation unit should not depend on the particular dimension on which a critical featural (target-nontarget) difference exists." (Müller, Heller & Ziegler, 1995, p. 3). In other words, processing on the dimension-based processing stage is independent of limited resources, and, consequently, is not susceptible to top-down modulation by cognitive (voluntary attentional) processes. (For this reason, the processes of the first stage are referred to as pre-attentive mechanisms.) Every feature target, no matter what dimension it is defined on, should be responded to equally fast in any given search trial.

However, at variance with the prediction of GS, in several experiments in which target predictability was manipulated, RTs were found to be slowed in a condition in which the target identity changed across consecutive trials compared to when it was repeated (Found & Müller, 1996; Müller, Heller & Ziegler, 1995; s.a., Treisman, 1988). These RT costs are inconsistent with the assumption of automatic processing of dimensional signals of GS. A mechanism accounting for dimension-based RT variations is proposed in the 'Dimension Weighting' account (DW; Found & Müller, 1996; Müller, Heller & Ziegler, 1995; Krummenacher & Müller, 2005), an account that can be conceived of as an extension to GS.

3.4 The weighting of dimensions

Due to the theoretical importance of the Dimension Weighting account for the present PhD thesis, the experiments, results and model will be discussed in more detail in this section.

The previous-trial effect (PTE)

Müller et al. (1995, Experiment 1) conducted a simple feature search experiment with two conditions: Search within one dimension (orientation) and a search across three dimensions (orientation, luminance, size). Distractors in both conditions were small grey bars. In the intra-dimension search condition, the target was always small and grey (as the distractors), but it differed from the distractors in orientation as it was either of horizontal, right- or left-tilted orientation relative to the vertically oriented distractors. In the cross-dimension condition, targets were small, grey, right-tilted bars (orientation target), small, black, vertical bars (luminance target) or big, grey, vertical bars (size target). Consequently, in search within one dimension there was no uncertainty about the target-defining dimension, by contrast, in cross-dimension search conditions the target dimension, at the beginning of a particular trial, was not predictable. A condition without any uncertainty as to the exact target-defining feature, with participants searching for the small, grey, right-tilted bar was run as an additional control condition. Participants' task was to indicate target presence or absence.

The results revealed parallel search in all three conditions, i.e., the search reaction time functions were flat. Importantly, however, the y-axis intercept of the cross-dimension search functions was substantially increased compared to the within-dimension (and feature) search functions by about 60 ms. Between the within-dimension and constant-feature control condition no reliable RT difference was found.

Müller et al. (1995) concluded that in a feature search task in order to detect the presence of a feature singleton in the display the dimensional information, not the feature value, is crucial. In other words, accessing the dimension-based saliency information underlies response selection and execution. The exact feature information seems not to play a key role (Found & Müller, 1996).

In another experiment, Müller et al. (1995, Experiment 2) replicated the findings of Experiment 1 and provided further support for their interpretation of the results of Experiment 1. Again, they tested within- versus cross-dimensional search, but in contrast to Experiment 1, the target was defined by a particular feature value. That is, participants were required to access feature representation in order to complete the search task correctly. In detail, in the within-dimensional condition, one pre-defined response was required if the singleton target was either a right-tilted or horizontal bar; a different response was required when the singleton item was a left-tilted bar. In other words, the targets had to be identified (target discrimination) and since all targets were defined within the same dimension participants were forced to access the representation of stimulus-defining features. In cross-dimension

search a right-tilted (size target) or black (colour target) bar required one response and a big (size target) bar required another response; that is, the stimulus-defining dimension was sufficient for a correct response. Results revealed RTs in the cross-dimensional conditions to be comparable to the RTs of Experiment 1 (there was a relatively small difference of about 20 ms); in within-dimension search, however, RTs were substantially increased (by about 70 ms) compared to RTs of Experiment 1.
Müller et al. concluded that accessing the target's dimensional identity is a prerequisite for adequate target detection. Therefore, the additional explicit demand for processing the target dimension, in cross-dimension search, does not affect RTs substantially. By contrast, the requirement to access the level of feature representations, as in the within-dimensional search of Experiment 2, causes a large RT cost.

Additional analyses by Müller and colleagues (1995) of the data of their Experiment 1 by means of 'inter-trial' analyses of RTs in the cross-dimension conditions revealed a significant RT benefit for targets that were defined in the same dimension across consecutive trials. The inter-trial analysis can be seen as a precise (local) measurement of RT differences caused by cross- versus within-dimensional changes of target-defining characteristics – simply due to the fact that only the inter-trial transitions of interest (repetition of the target-defining dimension and feature; repetition of the target-defining dimension with change of the target-defining feature; change of the target-defining dimension) are taken into account. Since the different target types are presented randomly in the sequence of trials in visual search experiments, in the cross-dimension search conditions, all the possible repetitions and changes of characteristics occur in approximately equal proportions given a large-enough number of trials. In order to limit the trial number, an alternative method is to generate the desired inter-trial pairs and insert the pre-generated pairs into the sequence of trials in randomized order. Relevant pairs of trials are analysed in such a way that any (relevant) trial *n* is related to its preceding trial *n*-1 and therefore the effects revealed in inter-trial analyses are referred to as 'previous-trial' (PTEs) or 'inter-trial' effects (ITE).

In Müller et al.'s (1995) study, only one particular (fixed) feature value was used per target-defining dimension in the cross-dimension search conditions. Therefore, Müller et al. could not examine whether the target repetition effect was due to repetition of the dimension or the feature.
If indeed the dimensional information is sufficient to complete a feature search task, feature repetitions or changes across consecutive trials are not expected to affect RTs. By contrast, dimension repetitions and changes should, respectively, expedite and slow RTs.
In order to further test the 'dimension' hypothesis, Found and Müller (1996) investigated feature singleton search performance in a task in which the targets were either (vertical) red or blue (target-defining dimension: colour) or (green) right- or left-tilted (orientation) bars; distractors were always

green vertical bars. Three different types of inter-trial transitions were examined: 1) repetition of the dimension and repletion of the feature across consecutive trails (inter-trial type referred to as same *D*imension, same *F*eature; sDsF), 2) repetition of the dimension, change of feature within this dimension (same *D*imension, *d*ifferent *F*eature; sDdF), 3) change of the dimension and change of the feature (*d*ifferent *D*imension, *d*ifferent *F*eature; dDdF).

Results of the study by Found et al. (1995) provided evidence for the prediction of dimension-, but not feature-based inter-trial RT effects. The pattern of previous-trial effects was such that there was inter-trial facilitation (± 30-40 ms) in consecutive trials containing a target defined in the same dimension but not necessarily by the same feature (sFsD and dFsD) compared to trials in which the target-defining dimension change across consecutive trials (dFdD). As an example, if a target was defined by colour on trial *n*, RTs were decreased if it was preceded by a target defined by colour (same dimension) in trial *n*-1 compared to when it was preceded by an orientation-defined target (different dimension) on trial *n*-1. Vice versa, when a colour target on trial *n* was preceded by an orientation target on trial *n*-1, RTs to the colour target were increased, compared to when it was preceded by another colour target in trial *n*-1 [4]. Importantly, there were no additional RT-benefits or -costs when the exact feature was repeated across trials within dimension (e.g. blue target on trial *n*; blue target on trial *n*-1) relative to when the feature value changed within dimension (blue target on trial *n*; red target on trial *n*-1). Consequently, the previous-trial effect – in feature search tasks – is dimension-based, not feature-based.

Dimension Weighting (DW)

Müller et al. (1995, 1996) used the findings of the cross-dimensional search and the dimension-based inter-trial effects as the basis for a theoretical explanation of search results they termed the 'Dimension Weighting' account (DW). DW is based on the architecture proposed by the GS model and can be seen as an extension of GS. The finding that RT are systematically modulated by the (inter-) trial history is at variance with the assumption that feature targets presented among homogenous distractors were detected on the basis of some early, purely saliency-based bottom-up detection mechanisms that is not susceptible to modulation. On the theoretical level, the previous-trial effects speak in favour of a 'weighting' at the time of allocation of limited attentional resources to different dimension-based modules that potentially process the target [5]. Target detection, according to DW, is thought to be affected by 'attentional' mechanisms modulating the distribution of processing resources that is modulated by stimulus characteristics.

[4] Due to the lack of baseline measurements in inter-trial analyses, previous-trial effects can only be expressed in a relative fashion: inter-trial dimension repetition causes RT-benefits compared to inter-trial dimension changes that cause (relative) RT-costs.

Müller and colleagues assume that, similar to GS, separate dimension-based saliency signals (computed on the basis of feature contrasts in the respective dimension-based modules) are pre-attentively integrated into an overall saliency, or priority map on which focal attention operates. In contrast to GS, instead of a mere summation of the dimension-specific saliency activations onto the priority map, according to DW, the dimensional saliency activities are ('attentionally') weighted prior to or during the integration onto the priority map (Figure 8). In other words, dimensional saliency is modulated and the strength of each dimension is increased or decreased according to its relevance. Dimensional relevance is mainly determined by the definition of the target in the previous trial. On the priority map, the amplified dimensional signal produces location-based activation that guides the focus of attention to the location of the highest activation.

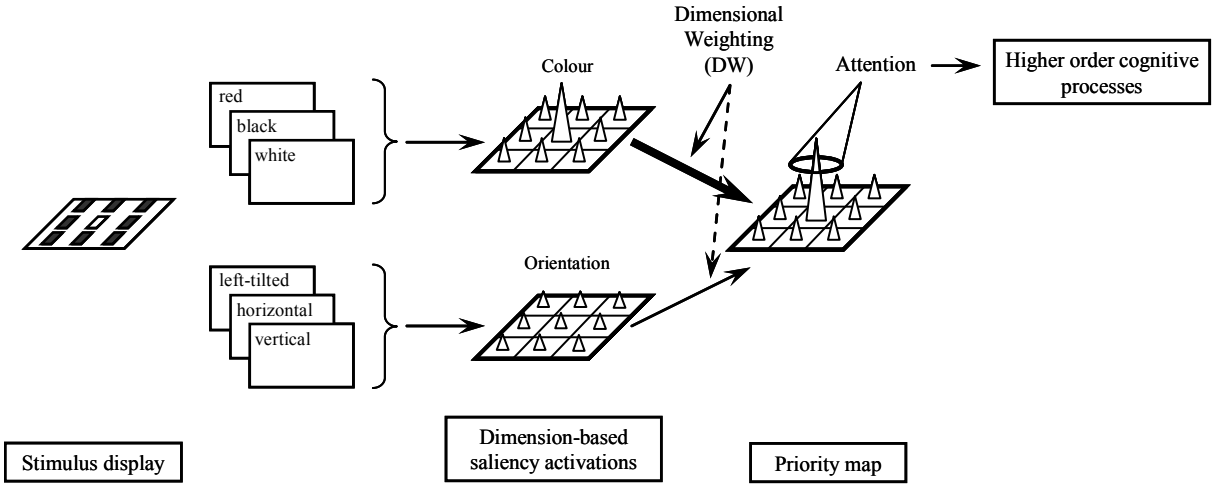


Figure 8. Functional architecture of the Dimension Weighting (DW; Found & Müller, 1996; Müller, Heller & Ziegler, 1995) account; the dimensional saliency activities are attentionally weighted prior to the integration onto the priority map.

[5] With reference to the terminology introduced by Duncan and Humphreys (1989, 1992), the limited resources are referred to as 'attentional weight' and, accordingly, the account proposed was dubbed the 'dimension weighting' (DW) account (Müller, Heller & Ziegler, 1995; Found & Müller, 1996; s.a. Müller, Reimann & Krummenacher, 2003; Krummenacher & Müller, 2005).

Importantly, the total amount of 'attentional' weight available is limited. The more weight is assigned to a particular dimension, the less weight remains for attribution to other dimensions. Higher weight allocated to one dimension is reflected by faster RTs to targets defined in the weighted dimension and slower RTs to targets defined in non-weighted dimensions.

The weight pattern established during or at the end of a given trial persists into the next trial, expediting search for a target defined in the same dimension. In detail, if the target-defining dimension remains the same across two consecutive trials (e.g., in intra-dimension search), the attentional weight pattern persists into the next trial and facilitates search for a target defined in the same dimension but not necessarily by the same feature. In contrast, when the target dimension changes across trials (e.g., in cross-dimension search), processing weight is shifted from one dimension to another in a time-consuming process causing a RT-increase relative to dimension repetition trials. One possible functional interpretation of the weighting process is that sufficient (limited) processing weight must be assigned to the dimension of interest to increase the saliency signal so that it exceeds a threshold that identifies saliency activation peaks to which then attention is directed.

The weighting of dimension-based saliency activation, although it is mainly controlled by dimensional stimulus definitions, can be modulated by top-down knowledge about the likely target dimension (Müller, Reimann & Krummenacher, 2003; see section 4.1).

4. Pre-attentive or post-selective locus of Dimension Weighting

According to the DW account (Müller et al., 1995, 2003; Found & Müller, 1996), the weighting of dimensions is thought to take place at an early, perceptual, pre-attentive stage of saliency computation. To be precise, the results of the attentional weighting process, the amplification of the weighted saliency signal is thought to take place before transmission of the dimension-based activations onto the priority map (Müller & Krummenacher, 2006; see also Folk & Remington, 1998). The DW account is agnostic as to the exact locus of the actual weighting process.

However, some researchers, most prominently Cohen and colleagues (Cohen & Feintuch, 2002; Cohen & Magen, 1999; Cohen & Shoup, 1997, 2000) and, along similar lines, Theeuwes and colleagues (e.g. Mortier, Theeuwes & Starreveld, 2005; Mortier, van Zoest, Meeter & Theeuwes, 2007; Theeuwes, 1992, 2004; Theeuwes, Atchley & Kramer, 2000; Theeuwes, Reimann & Mortier, 2006) argue in favour of an exclusively post-selective, response-related and against a pre-selective locus of modulations of search performance in feature (and compound) search (cross-dimensional-search and previous trial effects). Note also, that neither the DW account nor its theorists generally deny that weighting processes may take place at later, post-selective loci as well (Müller et al., 2003). In sum, these investigators argue in favour of (a) mechanism(s) assuming that modulation of perception occurs exclusively at post-selective, attentional, processing stages.

One reason for their assumption is that pre-attentive processes have traditionally been thought to be completely automatic in nature and not susceptible to any kind of modulation, be it implicit (i.e. inter-trial effects, stimulus probabilities, statistical learning) or explicit (i.e. expectations, voluntary settings). With the assumption of an early locus of weighting implicitly goes the acceptance that pre-attentive processes are penetrable, if not by all kinds of cognitive processes, but most likely by stimulus-driven factors.

That is, embedded in the question of whether dimension weighting, or, respectively, the effects explained by the DW model, take place at an early or late processing stage implies the theoretically relevant question of whether early processes are susceptible to modulation at all (see chapter 5).

In the present PhD project the ongoing debate between proponents of pre-attentive versus post-selective modulation(s) (weighting) of search processes is examined by means of two effects: The previous trial effect (PTE) and the redundant signals effect (RSE).

4.1 Locus of inter-trial effects

In the course of the debate on whether previous-trial effects arise on a pre-selective, perceptual or a post-selective, response-based stage, evidence was provided by different groups of researchers (for detailed discussions of the pre-selective position, see Müller et al. 2006, 2010; of the post-selective position, see Theeuwes, Olivers & Belopolsky , 2010; for a recent integrative review see Kristjánsson and Campana, 2010). In pre-selective theories such as the DW (Müller et al., 1995, 2003), RT-benefits following target dimension repetitions are assumed to be caused by facilitation at the level of early sensory coding of information of the repeated dimension – a pre-attentive process. In contrast, in post-selective theories such as the Dimension Action model (Cohen & Feintuch, 2002; Cohen & Magen, 1999; Cohen & Shoup, 1997, 2000) the repetition RT benefits are interpreted as the result of an expedition of processes at the level of the response preparation stage, i.e., after focal attention was attributed to a given search item, or, in other words, the item was selected – a process at the level of response preparation and/or response selection.

The Dimensional-Action model

In their response-based model, Cohen and Shoup (1997) argued that, similar to FIT and GS, the visual scene is represented in dimension-based modules, but that the modules are segregated not only on the level of perceptual analysis, but dimensions are also directly inputting to dimension-related response units (see early versions of FIT for a similar mechanism). According to the 'Dimension-Action' model (DA; Cohen & Shoup, 1997), each dimensional module (given the presence of particular feature in the visual field) computes an independent response decision; in other words, multiple response decisions (from the various dimensional modules) are available simultaneously. The role of attention is to control that only one of the response decisions at a time is transferred to the stage of executive functions; that is, only the deployment of attention to a particular item enables transmission of the computed response decision to the executive functions and action execution.

The results initially leading to the DA model (Cohen & Shoup, 1997) were found by using a modified 'flanker paradigm' (Eriksen & Eriksen, 1974). In the original flanker experiment - also known as 'response interference task' or 'flanker compatibility effect' - performance in a letter identification task (identity decision) was investigated dependent on the space between target and neighbouring flanker items (see section 2.1) and dependent on whether to which one of two sets the target belonged to.

The stimuli belonged to two sets each of which required a particular response (e.g., K and H required a right-hand, S and C a left-hand key press). The most important result was that participants responded faster in target-flanker congruent conditions, that is, in conditions in which target and flankers belonged to the same set (K H K) compared to target-flanker incongruent conditions, in which target

and distractors belonged to different stimulus sets (S H S). The RT compatibility effect was interpreted in terms of a congruency effect and was taken as evidence for selection at the response level (i.e., a selection bottleneck at the level of stimulus-to-response mapping). Although the flankers were irrelevant as to the task, participants were not able to ignore them (unless the distance between target and flankers was large enough; Eriksen & Eriksen, 1979; Miller, 1991; Yantis & Johnston, 1990).
In the flanker task used by Cohen and Shoup (1997), the response within stimulus set was varied additionally. The response to one of the two stimuli per set was assigned to the response-relevant dimension colour; the other stimulus of the set was assigned the response relevant dimension orientation. The responses in Cohen and Shoup's experiment were therefore determined by set (i.e. a red vertical and a blue right-tilted line versus a green vertical and a blue left-tilted line) and by dimension (i.e. colour or orientation). Cohen and Shoup (1997) showed congruency effects (faster RTs to targets sharing set identity with the flankers, and slower RTs to targets belonging to a different stimulus set than distractors) only if the target and the distractors were associated with the same dimensional response (i.e. a red target with red distractors - congruent, a red target with green distractors - incongruent) but not if flankers and target were assigned a different response-relevant dimension (i.e. a red target with right-tilted distractors - congruent, a red target with left-tilted distractors - incongruent). In the condition in which the target and the distractors belonged to different dimensional sets (multiple dimensions present in the display), multiple, separate, dimensional response preparations facilitated the discrimination of the target and abolished the flanker compatibility effect. In the condition in which the target and the distractors belonged to the same dimensional set (only one dimension being present in the display) however, only one response decision was activated and thus the target had to be discriminated from distractors on the basis of the set affiliation; distractors from a different set interfered with target discrimination, flankers from the same set did not.

Cohen and Magen (1999) explained the RT differences between within- and cross-dimensional search as reported by Müller et al. (1995; s.a. Found & Müller, 1996) by two factors.
First, in cross-dimension search, due to the multiple potentially target-defining dimensions, multiple response selection mechanisms are involved, all of which compete for attention. By contrast, in intra-dimension search, in which the target-defining dimension is constant within blocks of trials, attention is assigned to one and the same response. Thus, processing time is saved in constant-dimension compared to variable-dimension search, in which the correct action has to be established in an additional processing step.
The second factor affecting search performance in cross- vs. intra-dimension searches is inter-trial priming. Pre-knowledge or repetition of the target dimension primes the relevant dimension-specific response selection mechanism, resulting in a RT advantage relative to the search across dimensions in which response selection has to be shifted from trial to trial (previous trial effects of dimension change versus repetition). Note that Cohen and Magen (1999) refer to inter-trial effects as inter-trial priming.

With this formulation they implicitly assume an automatic generation of these effects. This term was introduced by Maljkovic and Nakayama (1994; see chapter 5) and refers to the impenetrability of pre-attentive processing.

In a series of experiments Cohen and Magen (1999) tested intra- and cross-dimensional search. In addition to the (dimensional) perceptual input, they also varied the stimulus-to-response mapping. In cross-dimension search, the target was either defined on the colour or orientation dimension (distractors were green and vertical), and observers had to indicate target presence or absence (the left-most key for left-tilted targets, middle key for red targets, and right-most key for target-absent trials). In intra-dimension search targets were defined in one dimension only (either colour or orientation) and the task required that, within the relevant dimension, the target feature had to be discriminated (left-most key either for left-tilted or blue targets and middle key either for right-tilted or red targets) in order to perform the task correctly (consequently, there were no target-absent trials). Cohen and Magen (1999) reasoned that if the RT differences between the intra- and cross-dimensional conditions were caused by perceptual processes, the required response should not affect search RTs; however, RTs to targets in the cross-dimensional condition should be slower to RTs in the within-dimension condition. By contrast, according to the DA model the pattern of cross- versus intra-dimensional RTs should be modulated by changes to the stimulus-to-response (dimension-to-action) mapping. In particular, responses to red and to left-tilted targets were compared.
Indeed, in Cohen et al.'s experiments, the cross-dimensional RT-costs were not only abolished, but the cross-dimensional search was even more efficient than intra-dimensional search (although the difference was in all cases statistically substantial).
Cohen et al. concluded that although there might have been previous-trial effects saving processing time in the intra-dimensional search conditions, there must have been another factor saving processing time in the cross-dimensional search conditions and that the amount of time saved by this process was higher than the benefits due to previous-trial effects. Of course the second factor is the constant (unique) dimension-to-response assignment within a given dimensional module in the cross-dimensional condition (two separate response selection mechanisms, one for each target dimension). In the search within one dimension on the other hand, in order to respond correctly, the feature identity had to be discerned and assigned to the correct response.
Note that with the experimental design used by Cohen et al., search in the cross-dimensional condition can be compared with absent-present search, whereas search within one dimension is comparable with discrimination search (cf. Found & Müller, 1996). According to the DW account (as also acknowledged by Cohen and Magen, 1999, p. 306) one could argue that rather than the current stimulus-to-response mapping, the required processing depth (determining [deeper] feature versus dimensional target identity) is the main aspect affecting search RTs.

Taken together, Cohen et al. (Cohen & Feintuch, 2002; Cohen & Magen, 1999; Cohen & Shoup, 1997, 2000) argue in favour of a late selection model that does not assume any kind of perceptual filtering of the input stimuli. In contrast to the assumptions of the DW account the entire visual input is processed up to the level of semantic representations. After focal-attention allocation, a late filter selects the information relevant for the current task.

Modulation of inter-trial effects by task factors

In contrast to Cohen and Magen (1999), there is also empirical evidence from studies using various search tasks that dimension-based inter-trial effects arise at an early stage of processing, even in tasks using modified stimulus-to-response mappings.

As an example, Found and Müller (1996) compared inter-trial effects in a feature search task requiring an absent-present decision (Experiment 1) with inter-trial effects to (physically) exactly the same stimulus material, but with the additional task demand to discriminate the relevant target-defining dimension (Found et al.'s procedure is similar to one used by Cohen and Magen (1999) with the difference that the dimension rather than the exact features had to be identified). Participants in Found et al.'s task had to decide whether the target was a colour (by depressing one out of two pre-defined response keys) or an orientation singleton (by depressing the other of the two keys). In both tasks, Cohen et al.'s feature and Found et al.'s dimensions search, more or less in the same orders of magnitude, participants were faster in dimension repetition compared to dimension change trials.

The results of Found and Müller (1996) were recently replicated by Gramann, Töllner, Krummenacher, Eimer and Müller (2007) in an investigation using electro-cortical potentials. Gramann and colleagues systematically compared stimulus-locked event-related potentials (ERPs) reflecting early perceptual, pre-attentive components (the P1-N1 complex, see, e.g. Luck, Woodman & Vogel, 2000), attentional (N2, e.g. Luck & Hillyard, 1994) as well as later components, including response- and memory-related (P3) processes of the three types of inter-trial transitions sDsF, sDdF and dD. Using the experimental design of Found and Müller (1996), Gramann et al. tested two conditions. In the first condition, observers searched for a colour (red, blue) or orientation (left-, right-tilted) singleton presented amongst homogenous distractors (Experiment 1; target-present vs. absent-present decision); in the second condition, the dimension defining the singleton had to be identified (Experiment 2; colour vs. orientation discrimination).

Behavioural as well as ERP results were comparable in both tasks. In particular, Gramann et al. found RT-costs in dimension change relative to dimension repetition trials in the manual response RTs. ERP-wise, dimension repetition versus change did not influence the P1 and N1 components, however, the N2 component was modulated by inter-trial dimension changes vs. repetitions. Gramann et al. (2007) concluded that the early components (P1 and N1) reflect perceptual processes within the focus of attention rather than feature contrast coding prior to attention allocation. Importantly, the N2 was

enhanced (more negatively pronounced) in dimension-change relative to dimension repetitions across trials (with or without feature repetition). Gramann et al. proposed that the modulation of the N2 amplitude reflects an additional processing step coming only into play when the target dimension changed across trials; in other words, the N2 might serve as a potential weight shift indicator. Further, investigation of the P3 component revealed inter-trial latency modulations in line with the RT pattern; onset latencies were prolonged for dimension change compared to repetition trials, (again) irrespective of target feature change or repetition. In the large time-window of the P3, several processes take place, some of which are associated with response requirements. Gramann et al. state that "one tentative interpretation [of the P3 modulation] might be that, after the detection of a change of the target-defining dimension, as reflected by increased negativities of the N2 component, attentional weights have to be shifted. The time-consuming redistribution of the dimensional weights might contribute to the P3 pattern in the present investigation …" (Gramann et al., 2007, p. 283f).

Importantly, Gramann et al. found strong evidence that attentional weighting is dimension-specific, rather than feature-specific in nature (see the dimension-based, but not feature-based modulation of the N2 and P3 components) and that weighting (at least to a certain degree) takes place prior to attention allocation and before the translation of target characteristics into response codes. The modulation of the N2 reflects weighting effects such as faster attention allocation to a repeated compared to a changed target dimension that take place before elicitation of the N2 component, so to speak, prior to the allocation of attention (selectively reflected by the N2). Consequently, the (re)assignment of limited attentional weight, in the case of a dimension change trial, takes place prior to allocation (of spatial) attention and is therefore associated with the generation of a dimension-based saliency representation. It seems though, that processes of attentional weighting are not exclusively occurring at the pre-attentive stage of processing: the redistribution of limited attentional weight seems to be partially reflected in the P3 as well. Gramann et al. conducted additional analyses on stimulus- and response-locked P3 components with the result that the (overall) amplitude differences disappeared in both the stimulus- and the response-locked P3 analyses. Thus it became clear that the P3 modulation was not response-driven, rather, the P3 reflects processes mediating between perceptual and response-related mechanisms. A similar interpretation was also proposed by Verleger, Jaskowski and Wascher (2005) and is very much in line with the assumptions of Müller et al. (2006; see later this section; see also Kingstone, 1992).

Note, however, that in the dimension discrimination tasks of Found and Müller (1996) and Gramann et al. (2007) some evidence for RT benefits in feature repetition trials in the colour, but not the orientation dimension, was found (see also Müller et al., 2003). To explain this pattern of inter-trial effects, Found et al. and Gramann et al. refer to Wolfe, Chun and Friedman-Hill (1995) and their idea that, in the colour dimension, feature contrasts may be computed in a number of 'sub-dimensions' coding input from the separable sets of colour receptors. Wolfe et al.'s idea is consistent with reports

of feature-specific grouping effects with colour, but not orientation targets (e.g. Nothdurft, 1992, 1993).
All in all, the results were comparable across detection (feature search) and dimension identifications (discrimination) tasks, and Gramann et al. concluded that in order to detect a visual feature at least implicit knowledge about its dimensional identity is required and that detection and discrimination tasks do not substantially differ from each other.

The assumption of pre-attentive dimension-based effects made by the DW account was also challenged by findings from (cross-dimensional) 'compound search' tasks. (Note that both challenges follow a similar line of argument.) In compound tasks (Duncan, 1985) the target-defining attribute is independent of the attribute determining the response. The target is detected on the basis of a conspicuous feature contrast (as in a feature search task), but the response is defined by another characteristic that is irrelevant for target detection. Figure 9 shows an example of a compound task, originally used by Theeuwes (1992); the target item is detected on the basis of its form (circle among diamonds) and the orientation (left-tilted vs. right-tilted) of the line drawn inside the target constitutes the response-relevant attribute.

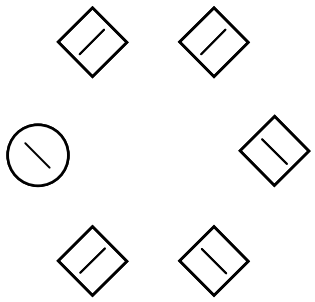


Figure 9. Example for compound stimuli (Theeuwes, 1992). The to-be-reported stimulus attribute (line orientation) is not the same as the attribute with which the target is detected (form).

The fact, that the features relevant for detection and response are not the same and independent of each other renders compound tasks very useful as it allows for the dissociation between the search-relevant and the response-relevant features; in other words, perception-based versus response-related component processes can be examined separately. According to the DW account, search performance in compound tasks should be the same as in feature detection tasks since both tasks involve the same pre-attentive processing steps. In principle, any performance difference between feature and compound search can be seen as evidence for late-selection accounts; these accounts assume that differences between the two tasks arise at the level of stimulus-to-response mapping.

As an example, Kumada (2001) found dimension-based inter-trial effects in target-present vs. target-absent decisions (Experiment 1a), but not in compound search tasks (Experiment 1b). In Kumada's compound task, the stimulus-to-response mapping required a differentiation between a left- and a right-pointing L-shape (the response was given by either a left or a right key-press). Therefore, only one (dimension-based) response selection mechanism was necessary to perform the task correctly. In Kumada's feature search task, the target was defined either in size, colour or orientation. Therefore multiple (dimension-based) response selection mechanisms are involved and subject to inter-trial modulation.
Other researcher also found only comparatively small (if any) previous-trial effects in compound search tasks (e.g. Chan & Hayward, 2007; Krummenacher, Müller & Heller, 2002; Mortier, Theeuwes & Starreveld, 2005 [Experiment 5]; Olivers & Meeter, 2006; Theeuwes, Reimann & Mortier, 2006). Some of these researchers therefore concluded that the mechanisms underlying target detection in feature and compound search differ on a general level (Chan & Hayward, 2007; Mortier et al., 2007); in particular, they suggest that the pre-attentive target selection process (thought to be automatic and impenetrable to cognitive factors) is completely independent of the later, post-selective response selection in compound tasks (Theeuwes, 1992).

However, in their meta-analysis Müller and Krummenacher (2006; see also Müller et al., 2010 for an updated recent take on the theoretical stance of dimension weighting) argue that the above assumption does not hold true. In their experiment, using Theeuwes' (1992) original compound stimuli, they obtained inter-trial effects, but only in those consecutive trials in which the response hand did not change. The target dimension change costs and repetition benefits, respectively, disappeared when the response attribute (also) changed in the relevant inter-trial sequences (see also Chan & Hayward, 2007; Krummenacher, Müller & Heller, 2002b; Olivers & Meeter, 2006; Pollmann, Weidner, Müller & von Cramon, 2000; Pollmann, Weidner, Müller, Maertens & von Cramon, 2006a). Müller and Krummenacher (2006) concluded that "although, statistically, there is no correlation between the two types of change (target-defining dimension, response attribute), the processing system "assumes" there is one. If the target dimension (the task attribute that becomes available first) remains unchanged, then the system implicitly assumes that the attribute on which the response is based will stay the same, too; that is, the unchanged response will be facilitated, and there is a cost if the response attribute actually changes. In contrast, if the dimension changes, the system cancels any prior assumption as to the response attribute to be expected, and starts processing from scratch. Whatever the explanation, the overall inter-trial effects in compound tasks are reduced because of some (in terms of event statistics wholly unsupported) linkage between dimension and response changes. This linkage may exist because, for the system, it may be easier to change both task "parameters", dimension and response, than to change just one parameter." (p. 507).

The interpretation of Müller and Krummenacher (2006) was recently strengthened by results coming from electro-cortical event-related potential analyses in a study by Töllner, Gramann, Müller, Kiss and Eimer (2008). The authors used a compound task, in which observers were first looking for a conspicuous colour (e.g. red) or shape (e.g. a square) singleton amongst blue circles. The response-relevant attribute was the orientation of a grating within the stimuli; horizontal gratings required responses with one, vertical gratings responses with the other hand. In addition to behavioural analyses, Töllner et al. recorded electroencephalograms (EEG) and analysed ERPs associated with dimension repetition vs. changes and response repetitions vs. changes. Consequently, in their experiment, the authors tested four (inter-trial) conditions of interest: same Dimension, same Response (sDsR), same Dimension, different Response (sDdR), different Dimension, same Response (dDsR) and different Dimension, different Response (dDdR).

Two ERP components were selected to distinguish between perception-based and response-related modulations; the N2pc and the LRP component.

The N2pc (lateralised N2 posterior-contralateral) is a negative-going deflection with a maximum over visual areas (electrode sites PO7, PO8; PO = posterior, occipital position) of the hemisphere contralateral to the attended stimulus location. In other words, the N2pc for a given hemisphere is more negative when a search item (object) is attended in the contralateral compared to the ipsilateral visual field. The N2pc was observed to peak between 150 ms and 300 ms after stimulus-onset and it is interpreted to reflect attentional selection of target items amongst distractors (the focusing of spatial attention onto the target location) on the basis of perceptual target-defining attributes (e.g. Eimer, 1996; Hopf, Boelmans, Schoenfeld, Heinze & Luck, 2002; Luck & Vogel, 1997; Luck & Hillyard, 1994; Woodman & Luck, 1999).

The N2pc marks the transition from perceptual, pre-attentive information extraction to the stage of attentional selection of the target. Factors influencing pre-attentive processing, such as inter-trial effects (as proposed by DW), are expected to be reflected in the latency and possibly also in the amplitude of the N2pc. In detail, in target dimension repetition trials, the N2pc is expected to peak earlier and (possibly) to show larger amplitudes compared to inter-trial transitions in which the target defining dimension is changed. The two modulations should be independent of the change or repetition of the response-relevant features of the target; that is, the ERP-related predictions allow for a differentiation of effects related to the allocation of focal attention (N2pc) and response-related effects (LRP). The predicted pattern of ERP effects therefore differs from the predicted pattern of behavioural RTs; here, change or repetition of the target-defining dimension modulates the effect of response repetition vs. changes. In contrast, if previous-trial effects should not arise at pre-attentive, but later stages of processing, no inter-trial modulation of the N2pc is expected and the N2pc should be the same for target dimension repetition and change trials.

The second ERP component relevant for the present project, the LRP (lateralised readiness potential) is observed over motor areas (electrode sites C3, C4; C = central position) contralateral to the side of

the response hand side. The LRP of one hemisphere is more negative when movements of the contralateral compared to the ipsilateral response hand are prepared. The LRP modulation is observed even when the response is not executed. The LRP was interpreted as a marker for preparation (stimulus-locked LRP) and execution of motor responses after response selection has been completed (response-locked LRP) (e.g. Eimer, 1997; Eimer & Coles, 2003; Hackley & Valle-Inclán, 2003). It is commonly agreed that the LRP cancels out any perceptual and / or cognitive processes. That is, the LRP can be analysed in two ways: Response-locked LRPs (rLRP) reflect response activation and execution processes, stimulus-locked LRPs (sLRP) are determined by both the selection and analysis of the target and the selection and preparation of the response prior to response-activation. sLRP reflects an intermediate processing stage between attentional target selection (indexed by the N2pc) and response production (indexed by the rLRP) (Töllner et al., 2008; for methods to distinguish the motor stages, see Leuthold, 2003).

In terms of analysis methodology, the N2pc and the LRP are extracted from overall ERP signals by subtraction of the ipsilateral from the contralateral waveforms at corresponding electrode sites with respect to lateralised target presentations or uni-manual (hand) responses, respectively (Eimer, 1998; Eimer & Coles, 2003; Hackley & Valle-Inclán, 2003). Both components are then determined independently as the maximum negative deflection within pre-defined time windows (for the N2pc usually the window between 150 to 350 ms post-stimulus onset is used: for the LRP the time-window is larger, covering the entire range from stimulus-onset to response execution plus a baseline after response execution).

Taken together, in terms of the assumption of a double dissociation, if previous-trial effects were either (purely) perceptual or response-based in nature, one would expect to find modulations of either the N2pc (perceptual component processes), but not of the LRPs (response component) as evidence for a perceptual account, or, the other way round, no modulations of the N2pc, but the modulations of the LRPs as evidence for a response-based account. In their recent study, Töllner et al. (2008) expected the N2pc to be modulated by dimension repetition versus change inter-trial transitions and the rLRP to be affected by response repetitions versus response changes. The critical question in their study was whether the rLRPs would also be modulated by dimension repetitions compared to–changes. Such an outcome was in contradiction to the assumptions of DW (Müller et al., 1995, 1996), because previous-trial effects are thought to arise prior to response-related stages. However, this pattern would constitute support for late-selection models such as the DA (Cohen & Shoup, 1997). Additionally, by analysing the sLRP component, the processes responsible for the interaction (linkage of expectancies) between repetition versus changes of the target-defining dimension and the response as shown by Müller and Krummenacher (2006; see above) were investigated.

Behavioural results of Töllner et al.'s experiment were comparable to the RT patters reported in earlier studies (Krummenacher et al., 2002b; Müller & Krummenacher, 2006; Pollmann et al., 2000, 2006a;

see also Chan & Hayward, 2007 and Olivers & Meeter, 2006): targets in dimension repetition trials were only responded to faster compared to dimension change trials if the response was repeated across consecutive trials as well.

ERP-wise, the amplitude of the N2pc was substantially enhanced and the N2pc latency significantly shortened in dimension repetition relative to dimension change trials. These results can be interpreted as more efficient and faster allocation of focal attention (Eimer, 1996; Woodman & Luck, 1999) in dimension repetition compared to dimension change trials (Töllner et al., 2008). Both the latency and the amplitude effects were independent of the repetition or change of the response feature across trials. The perceptual PTE was shown to be independent of the required response, in other words, the expedited target detection in dimension repetition trials was determined by perceptual attributes and not by response-related characteristics. That is, the finding is in line with the assumptions of the DW account. Töllner et al. proposed that the delayed peak latency in dimension change relative to repetition trials possibly reflects the weight shift from the old to the new target dimension.

Importantly, the latency of the rLRPs was not modulated at all, that is, neither by dimension, nor by response changes; however, rLRP amplitudes differed systematically with inter-trial transition and were substantially enlarged in the form of an increased negative deflection for response change compared to response repetition trials. Note that according to Eimer and Coles (2003) experimental manipulations of the rLRP are expected to affect onset latencies, but not amplitudes (the longer the response activation and execution process takes to complete, the earlier is the rLRP onset). At variance with Eimer et al.'s reasoning, Miller and Low (2001) reported that rLRP amplitudes were enhanced under high-demand conditions (see also Karayanidis & Michie, 2006). Töllner et al. interpret the rLRP amplitude modulation as potentially reflecting weight-shifting processes of response activation and execution in trials in which the response is changed. In case the response is repeated, the pre-existing response activation requires less additional activation to reach the motor threshold and to generate a response. However, the important finding is that, in marked contrast to the N2pc modulation, dimension changes or repetitions did not influence rLRPs.

The analysis of the sLRP component revealed the fastest onset latencies were associated with sDsR, followed by dDdR, sDdR and dDsR inter-trial transitions. All of the sLRP onset latency differences were found to be significant. These results show that it is inadequate to assume that there exist separate perceptual attentional and response-related attentional processing stages. Rather, as suggested by the pattern of behavioural RTs, there is an intermediate stimulus-to-response translation or response selection stage the operation of which differs between the conditions. By means of a heuristic model Töllner et al. (2008; p. 540) were able to predict the duration of the intermediate stage (overall RTs = perceptual N2pc latencies + response selection + response production rLRP amplitudes [indirectly transformed into latencies]). The prediction that whenever one of the attributes changed (sDdR, dDsR), processing at the response selection stage should be prolonged was in line with the results of sLRP onset latencies. Similar to Müller and Krummenacher (2006), Töllner et al. concluded that "this

[modulation of the response selection stage] may be explained by postulating that the response selection stage assumes a correlation between the two types of change, even though dimension and response changes occurred independently of each other in the event statistics." (Töllner et al., 2008, p. 540).

Taken together Töllner et al. (2008) found that irrespective of the required (motor) response, dimension changes were reflected in shortened latencies and enhanced amplitudes of the N2pc component and that irrespective of dimension changes, (motor) response changes were accompanied by an enhanced amplitude of the rLRP; however, there was also modulation of an intermediate stage involving target analysis and response selection. Taken together, these findings provide evidence for a pre-selective mechanism to explain dimension-based inter-trial effects. However, as the sLRP results show, a later, response-based contribution to the effect cannot be ruled out completely.

To sum up the findings discussed so far, it was shown that the processing times of pre-attentive perceptual (saliency generation) and post-selective (stimulus analysis and response selection) component mechanisms are not strictly additive in compound tasks (as assumed by post-selective accounts); rather, perceptual and response processes are linked by expectancies about the perceptual and response-related characteristics of the search target (see, Kingstone, 1992; linkage of expectancies). The conclusion that dimension-specific inter-trial effects arise exclusively at post-selective, response-related processing stages is therefore not tenable. Note that this conclusion also applies to the findings of modulated dimension-based inter-trial effects in Cohen and Magen's (1999) discrimination tasks. The task these authors (as well as Found and Müller, 1996, and Gramann et al., 2007) used was, properly speaking, a compound task. First participants had to detect the target (recall that the target location is coded by a dimension and feature-unspecific overall saliency signal) and then to discern the target feature (or dimension, respectively) in order to be able to respond correctly. In line with this rationale it can be assumed that Cohen and Magen's reduced/abolished inter-trial effects (in the cross-dimensional search) vary in response repetition relative to response change trials; that is, their inter-trial effects are expected to be found (exclusively) in response repetition trials. The conclusion of Gramann et al. (2007) that detection and discrimination tasks do not substantially differ from each other provides further support for the assumption that the processing mechanisms of detection and compound tasks are highly similar.

Krummenacher, Müller, Zehetleitner and Geyer (2009) recently accounted for the differences in the magnitude of inter-trial effects in detections versus compound search tasks by an argument based on the distribution of spatial saliency signals. Krummenacher et al. argued that while in feature detection tasks response generation and execution does not require the allocation of focal attention to the target (e.g. Krummenacher, Müller & Heller, 2002b; Müller & Krummenacher, 2006), rather, the target is detected on the basis of an above-threshold (overall) saliency signal; in contrast, in compound tasks,

focal attention needs to be allocated to the target in order to gate the (minute) response-relevant attribute to higher-order cognitive processes. The spatially limited focus of attention prevents information from nearby distractor items from interfering with the processing of the target-related information. Krummenacher et al. therefore argued that, in detection tasks, inter-trial effects should not be modulated by varying distances between target locations in consecutive trials. By contrast, in compound tasks, the spatial locations of consecutive targets may give raise to space-based inter-trial effects to arise, because the time-consuming re-allocation of (spatial) focal attention across consecutive experimental trials overrides dimension-based inter-trial effects. In two experiments, Krummenacher et al. (2009) compared dimension-based and space-based (i.e., effects based on the distance between target locations in trial *n* and trial *n-1*) inter-trial effects in feature detection and compound tasks. They found strong evidence for a weighting mechanism that is space-based in compound tasks, while, in detection tasks, weighting is dimension-based. They concluded, that the space-based weighting seems to suppress the effects of dimensional weighting on the level of the priority map and that the suppressive effect is scaled by the distance between the location of focal attention in the preceding (trial *n-1*) and the current (trial *n*).

Mortier, Theeuwes, and Starreveld (2005) reignited the debate on the locus, early or late, of inter-trial modulation by pointing out two potentially important aspects. In their study, they claim that if dimension-specific inter-trial effects originate at processing stages located after completion of search (i.e., after processing of the target by focal attentional) dimension repetition/change effects should arise even in tasks that do not require search for a target. Mortier et al. tested this prediction in a study in which they compared two tasks that differed relative to their respective demands on target selection, a singleton search task and what they refer to as a non-search task. In the *singleton search* task, observers had to discern the presence (vs. absence) of a singleton target in displays with variable numbers of distractor items. Mortier et al. compared two (blocked) search conditions: (i) *intra-dimension search*, where the singleton, when present, always differed from distractors in colour; and (ii) *cross-dimension search*, where the singleton differed in colour, shape, or size.
The *non-search* task was designed as to eliminate the search component by presenting one single item only on every experimental trial (for a similar procedure, see Goolsby & Suzuki, 2001). On some (non-search) trials, the presented stimulus was a small grey circle (which was identical to the distractor items of the search task). The circle was also used as a distractor in the non-search task and required a 'target-absent' response. If the presented item was different from the distractor in whatever visual attribute (i.e., if it was not a small grey circle), a 'target-present' response was required. In analogy to the search task, in the non-search task, there were two (blocked) conditions: (i) an *intra-dimension* condition, where the critical difference was always in the colour dimension, and (ii) a *cross-dimension* condition, where the difference could be in the colour, shape, or size dimension. Thus, in brief,

Mortier et al. (2005) compared performance in two tasks in which items had to be selected (search task) or the search component was minimized or absent (non-search task).
In both the search and non-search tasks, participants responded faster to the target stimulus in the intra-dimension than in the cross-dimension condition. In the cross-dimension conditions of both tasks, RTs were faster when the relevant dimension was repeated across consecutive trials compared to when the dimension changed (i.e., significant dimension repetition benefits were observed in both search and non-search tasks). Mortier et al. took the significant dimension repetition benefits in the non-search task to argue in favour of a post-selective account of dimension-based effects. In detail, they argued that "the present study showed that specific effects typically attributed to top-down guidance of search processes, also occur in conditions in which there is no search" and they concluded that "these effects are the result of later processes, presumably response selection." (Mortier et al., 2005, p. 556).

In summary, based on the similarity of the behavioural data from their search and non-search tasks, Mortier et al. (2005) interpreted the dimension repetition benefits as originating from post-selective processing stages in both tasks. However, instead of assuming a single (and as in the case of Mortier et al., post-selective) dimension weighting system, one could also assume the existence of multiple (i.e., two) weighting mechanisms operating at different processing stages. One mechanism would modulate saliency signal computation or integration as proposed in the DWA and generate the dimension repetition benefits in search tasks. A second weighting mechanism would modulate post-selective processes and produce the dimension repetition benefits in non-search tasks. Note that the notion of multiple dimension weighting mechanisms (operating on different stages of processing) is compatible with the DW account. DW assumes that at least part of the dimension repetition benefits observed in *singleton detection* tasks stems from the weighting of dimension-specific saliency signals, without excluding the possibility that there may be other, post-selective processing stages sensitive to the inter-trial sequence of perceptual dimensions (e.g. Krummenacher, Müller & Heller, 2001; Müller & Krummenacher, 2006; Töllner et al., 2008).

Experiment 1: Inter-trial effects in visual search and discrimination tasks: separable pre-attentive and post-selective effects

Purpose of the present study

The present study was designed to examine whether the dimension repetition benefits in the search and non-search tasks originate from the same, or from different – pre-attentive and, respectively, post-selective – stages of processing. A pre-selective locus of dimension repetition benefits would predict that the inter-trial effects in a search task are dimension-specific in nature (i.e., there should be no cost

of a feature change within a repeated dimension) because feature identity plays no role in the (pre-attentive) computations that single out the target amongst the homogeneous distractors. By contrast, a discrimination task with a single stimulus (along the lines of Mortier et al., 2005) may well involve a feature-specific component, because the (post-selective) discrimination required involves feature-based matching of the target against a standard held in working memory. Recall that in the discrimination (non-search) task of Mortier et al. (2005), the single stimulus was to be compared against one (or multiple) standard stimulus (stimuli). The probably most efficient strategy was to compare each single search item against the (non-target) small grey circle, which (in case of a match) requires a 'target-absent' response. If the current item was different from the standard (in whatever visual attribute), the alternative 'target-present' response was required. However, the fact that Mortier et al. (2005) found a dimension repetition benefit indicates that observers do not necessarily apply the efficient strategy outlined above, i.e., they do not 'simply' trigger the 'target-present' response in the case of a mismatch of the currently processed item with the non-target standard. (Probably, it would be cognitively more demanding to suppress the representation of the stimulus visible on the search screen than it is to change the comparison standard across trials. It is also likely that it is not, or hardly, possible to associate one particular template [small grey bar] with two different [target-absent, target-present] responses.) Rather, participants appear to check the identity of each of the items and to trigger the response associated with it. Most likely, the task involves a comparison of the current stimulus against the different templates held in working memory by a dimension-based mechanism – that is, the matching process is likely to switch from one possible target-defining feature in one dimension to another possible feature within the same dimension (e.g., check all colour features first), before it switches to another possible feature in a different dimension (check shape features next, etc.). Consequently, there would be feature-specific effects in the discrimination task (in addition to dimension-specific effects [6] – but not in the search task where detection of an above-threshold saliency signal is sufficient for the selection of the correct response on the basis of dimension-based saliency signals; that is, dimension-specific effects are expected in the search task. By contrast, on a unitary account assuming that all the dimension-based (and feature-based) effects originate at a post-selective stage of processing, there should be feature-specific effects in both the search and non-search task. (Note that Mortier et al., 2005, did not analyze feature-specific inter-trial effects in their study.)

[6] Note, that the expected feature-based inter-trial effects should differ from those found by Found and Müller (1996) or Gramann et al. (2007) in such a way, that they should not be colour specific, but also evident for orientation features.

Based on the above reasoning, the prediction of feature-specific effects in the non-search task of Mortier et al. (2005) is also consistent with Huang and Pashler's (2007) recent Boolean Map Theory (BMT) of how visual (feature) information accesses awareness. Huang and Pashler propose that gating sensory information to conscious awareness requires the construction of a Boolean map representation. BMT is based on three key assumptions: (i) conscious visual information is indexed by location, that is, a specific feature is bound to a particular location of the visual field; (ii) at any given point in time, a Boolean map codes one feature value per dimension only and one dimension only (e.g., colour: red, or orientation: vertical); and (iii) all objects characterized by the same feature (e.g., colour: red) are represented in one Boolean map (multiple location coding). Importantly, in the context of the present study, a Boolean map is generated either from information coded in feature maps, or by combining (via the operations of intersection or union) already constructed Boolean maps. There are two starting points for constructing Boolean maps: Starting with a feature value returns a map with all the locations at which the particular feature is present (feature-location mechanism); starting with a location returns the feature value for the particular location (location-feature mechanism). Top-down controlled selection of a particular feature for comparison with a template is achieved exclusively by the feature-location routine.

With regard to the *non-search* task of Mortier et al. (2005), this would imply that observers start template matching with one feature (template) in one dimension (e.g., is the item at the selected location red?), then proceed to the next feature in the same dimension (is it blue), and then change dimension (is it left-tilted?; right-tilted?) and so on, until either a match is detected (respond 'target-present') or all templates have been checked without returning a match (respond 'target-absent'). Assuming that observers start template matching with the feature (in the dimension) that returned a match on the previous trial, this would generate both feature- and dimension-specific inter-trial effects. While the number of steps involved in Boolean map construction could, thus, explain performance (inter-trial effects) in the non-search task, BMT cannot as such account for the evidence of co-activation of detection responses by target signals defined redundantly in multiple dimensions (compared to targets defined in one dimension only) in the singleton *search* task. However, assuming that target detection does not require that the target-defining features are consciously represented, but rather that target-present responses can be triggering on the basis of a pre-selective saliency representation (along the lines proposed by DWA), the puzzle can be solved (this has been acknowledged by L.Huang, personal communication to Joseph Krummenacher, July 19th, 2008).

The present experiments were designed to examine for dissociations in processing between the two types of task, in order to decide whether or not an account assuming a unitary, post-selective source of inter-trial effects in search and non-search tasks is tenable.

Overview of Experiment 1

Experiment 1 compared the pattern of inter-trial effects in the performance between singleton feature search (e.g., Found & Müller, 1996), where targets were presented (on target-present trials) at an unpredictable (variable) position within an array of homogeneous distracters, and a non-search task (Mortier et al., 2005), where the same targets (or, on target-absent trials, a distractor) were presented in isolation at a fixed position in the display centre, thus effectively removing the search component from the singleton feature search task (see also Goolsby & Suzuki, 2001). The aim of the comparison was to examine whether the search task would only produce dimension-specific inter-trial effects, whereas the non-search task would produce dimension- and feature-specific effects. For the reasons elaborated above, dimension-specific effects would be indicative of a response selection and execution based on pre-selective saliency activity, whereas feature-specific effects would be indicative of post-selective discrimination processes. – Two further conditions were tested in Experiment 1: A multi-item condition (as in the search task) with the target position held constant (at the display centre); and a single-item condition (as in the non-search task) with the target position variable. These conditions were introduced to allow for the effects of feature contrast independent of location variability and target location variability independent of feature variability to be examined.

Method

Participants. Twelve observers (five female; age range 23 to 29 years, median age 25.5 years) participated in Experiment 1. All had normal or corrected-to-normal vision, all reported normal colour vision. Participants were paid at a rate of CHF 10 (approximately $ 9) per hour or received course credits. All observers were naïve as to the purpose of the experiment; most of them had no previous experience with visual-search experiments.

Apparatus, stimuli, task. Experiment 1 compared two basic conditions: multiple item (feature contrast saliency) and single item (no feature contrast saliency) displays. In each of the two conditions, the target location could be either randomly varied across trials or constant (display centre). In the multiple-item conditions, displays comprised of a 7×7 item array of items. On target-absent trials, a homogenous array of distractor items (green vertical bars) was presented; on target-present trials, one of the distractors was replaced by a singleton feature target (the target was defined either on the colour dimensions: red vertical bar, blue vertical bar; or the orientation dimension: green 45° left-tilted bar, green, 45° right-tilted bar). In the single-item conditions, the display contained only one item: a non-target (green vertical bar) or one out of the four possible targets (red vertical, blue vertical, green 45° left-tilted, green, 45° right-tilted bar). That is, the possible non-targets and targets were the same as in the multi-item conditions and the required the same target-absent or, respectively, target-present responses.

Display items (bars) subtended approximately 0.9° of visual angle in height and 0.2° in width. Bars were oriented vertically or tilted 45° to the left or right, respectively, relative to the vertical. Display

items were coloured in isoluminant green (CIE x,y chromatic coordinates 0.311, 0.578; luminance 1.6 cd/m²), red (CIE 0.596, 0.358; 1.6 cd/m²) or blue (CIE 0.148, 0.065; 1.6 cd/m²) and presented on black screen background. Display items in the multiple-item conditions were arranged on a virtual rectangular grid consisting of 7 × 7 cells, with each cell subtending 2.2° in height and width. Item positions were slightly jittered vertically and horizontally by a maximum of 0.6° of visual angle relative to the cell centre. Minimum (and maximum) distance (measured as the distance between centres of gravity) between display items was 1.1° (3.3°) both horizontally and vertically. The entire display subtended between 16.0° of visual angle vertically and horizontally. In the multiple-item condition with a variable target location, target presentation was restricted to the inner 5 × 5 grid cells to equate local feature contrast effects (observers were not informed about the restriction). In the multiple-item condition with a constant target location, the target appeared always in the display centre. In the single-item conditions, only one stimulus, either a target or a distractor, was presented, either at variable locations in one of the 5 × 5 cells of the virtual grid (underlying multi-item displays) or at the constant display centre location.

Stimulus presentation, timing, and response recording were controlled by a Pentium PC running under the Windows XP operating system and using the “Cogent 2000” toolbox (www.vislab.ucl.ac.uk/Cogent/) for MATLAB (Mathworks, Inc.). Stimuli were presented at 100 Hz on a 19" CRT monitor (Phillips Brilliance P202), at a screen resolution of 1280 × 1024 pixels. Observes viewed the display from a distance of 70 cm. Observers responded by pressing one of the control (Ctrl) keys in the lower left and right parts of a standard keyboard placed at a comfortable distance on a table in front of the observer.

Observers’ task was to indicate, as quickly and accurately as possible, whether a target item was present in the display or not. Prior to the experiment, observers were carefully informed about the identity of distractor and target items: distractors were always green vertical bars; targets were either red (vertical), blue (vertical), 45° left-tilted (green), or 45° right-tilted (green) bars. Observers were to press the right control key to indicate target presence, and the left key to indicate target absence.

Procedure and timing. Each trial started with the presentation of a fixation point (a circle with a diameter of approx. 0.2° of visual angle) for 570 ms; over this period, the luminance of the fixation marker increased gradually from background luminance to 1.6 cd/m² and then gradually decreased again to background luminance. The screen remained blank for a period of 200 ms after the disappearance of the fixation point to avoid forward masking in the single-item condition. The response-relevant display consisted of the simultaneous onset of all the items in the multiple-item condition, or the presentation of an isolated item in the single-item condition. Displays remained visible until the observer had responded target-present or target-absent. The response was followed by an inter-trial interval with a blank screen for 400 ms. At the end of each block participants received feedback on their mean RTs and error rates.

The following four experimental conditions were completed by all participants: Multiple items, variable location (MIv); multiple items, constant location (MIc); single item, variable location (SIv); single item, constant location (SIc). That is, both in the multiple and the single item conditions, target locations were either constant or variable. In the constant-location conditions, the target was presented at the display centre (i.e., at the location of the fixation point), on multiple-item trials, the target (at the centre) was surrounded by distractors, while it was the only item on single-item trials (see Figure 10, top left and right hand panels). In the variable-location conditions, the target was presented at a randomly chosen location within the inner 5 x 5 cells of the virtual display grid (see Figure 1, bottom left and right hand panels).

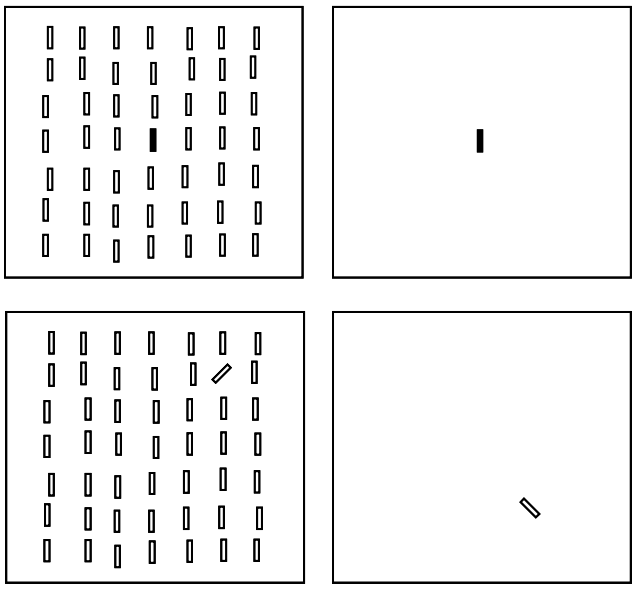


Figure 10: The four experimental conditions: multiple and single item with constant target location (top left and right hand panels) and multiple and single item with variable target location (bottom left and right hand panels).

The order of conditions was counterbalanced across the twelve observers. Half of them began the experiment with a multiple-item condition; the other half with a single-item condition. Of the six participants with multiple-item display as the first condition(s), three started with the constant-, the remaining three with the variable-location condition, conditions were controlled accordingly for the six participants who started with a single item condition.

Each of the four conditions comprised of 10 blocks of 94 trials, for a total of 3760 experimental trials. Targets were presented in 60% of trials (target-present trials); in the remaining 40%, no target was presented (target-absent trials). The definition of the target type (colour: red, blue; orientation: left-, right-tilted), in target-present trials, was equally probable. At the beginning of each condition, a training block of ten trials was presented to familiarize observers with the task. Before the experiment, participants were given the opportunity to become familiar with the different task by performing at

least two blocks of ten trials in each condition. Observers were free to take a break between blocks. The experiment was run in two sessions, with two experimental conditions completed per session; two sessions, either the multi-items variable- and constant-location conditions, or, respectively, the single-item variable- and constant-location conditions, were run on the same day. Each of the two sessions took about 60 min to complete.

Results

RTs shorter than 200 ms and longer than 1200 ms were excluded from analysis (0.3% of all trials), as anticipatory or exceedingly slow reactions, respectively. Additionally, RTs deviating from mean RTs by more than three standard deviations were excluded from analysis separately for each participant and each of the four conditions (less than 1.1 % of all trials). Data were analyzed using repeated-measures analyses of variance (ANOVAs); Bonferroni correction was used for multiple comparisons of condition means where necessary.

Errors. Mean error rates for target-absent (false alarms) and target-present trials (misses) trials were subjected to a repeated-measures ANOVA with the factors: display (multiple items, single item), target location (constant, variable location), and error type (miss, false alarm). The ANOVA revealed the main effects of display [$F(1,11) = 32.719$, $p < .001$] and error type [$F(1,11) = 24.782$, $p < .001$] to be significant. Target location did not affect error rate [$F(1.11) < 1$, n.s.]. Error rates were significantly lower in multiple-items than in single-item conditions (5.1% vs. 6.7 %), and significantly more false alarms were made than misses (7.7% vs. 4.1%).
Moreover, the interaction between display and error type was significant [$F(1,11) = 34.798$, $p < .001$]. Miss rates did not differ between conditions with a single item and multiple items (4.2% vs. 4.0%; $t(11) < 1$, n.s.). However, the proportion of false alarms was significantly larger in the single-item than in the multiple-items conditions (9.3% vs. 6.2%; $t(11) = 7.701$, two-tailed $p < 001$). The false alarm rate was significantly higher than the miss rate in the single-item conditions (9.3 % vs. 4.2 %; $t(11) = 6.675$, $p < .001$). The difference between the two types of errors in the multiple-items conditions, though smaller than in the single item conditions, was also reliable (4.0% vs. 6.2%; $t(11) = 2.782$.$p < .05$). Still, although the false-alarm rate is overall higher than the miss rate (main effect of error type), this effect is mainly due to the high-false alarm rate in single-item conditions.

Reaction times. Mean target-absent and -present RTs were analyzed by separate repeated-measures ANOVAs, as well as in a combined ANOVA. The combined ANOVA, with the factors trial (absent, present), display (multiple items, single item), and target location (variable, constant), was conducted to compare target-present (pooled data of colour and orientation trials) and -absent RTs. Overall, multiple-item displays were responded to some 10 ms faster than single-item displays (389.7 vs. 398.0 ms) [non-significant main effect of display: $F(1,11) = 1.298$, $p > .25$]. The main effect of trial was

significant [$F(1,11) = 25.155$, $p < .001$]: target-present RTs were overall faster than target-absent RTs (382.2 vs. 405.5 ms). The main effect of target location was also significant [$F(1,11) = 88.705$, $p < .001$]: RTs were slower overall when target location was variable rather than fixed (402.8 vs. 384.9 ms).

Importantly, the interaction between display and trial was significant [$F(1,11) = 15.312$, $p = .002$]. Target-present RTs were significantly faster with multiple-items than with single-item displays (370.7 vs. 393.6 ms; $t(11) = 3.417$, two-tailed $p = .006$), while target-absent RTs did not differ between the two display conditions (408.7 vs. 402.3 ms; $t(11) < 1$, n.s). With multiple-items displays, target-present RTs were significantly faster than target-absent RTs (370.7 vs. 408.7 ms; $t(11) = 5.616$, two-tailed $p < .001$); by contrast, with single-item displays, target-present and -absent RTs did not differ significantly (402.3 vs. 393.6 ms; $t(11) = 1.717$, two-tailed $p = .114$).

An ANOVA of the target-present RTs, with the factors display (multiple items, single item), target location (variable, constant), and target dimension (colour, orientation), revealed all three main effects to be significant. Multiple-items displays were responded to 22.9 ms faster than single-item displays (370.7 vs. 393.6 ms) [$F(1,11) = 11.676$, $p = .006$]. Variable target location produced slower RTs than constant target location (390.5 vs. 373.9 ms) [$F(1,11) = 58.214$, $p < .001$]. And colour targets were responded to faster than orientation targets (373.9 vs.390.4 ms) [$F(1,11) = 30.955$, $p < .001$]. Of the interactions, only target location x dimension was reliable [$F(1,11) = 10.932$, $p = .007$]: RTs to colour targets were somewhat less affected by variability, versus constancy, of target location (379.6 vs. 368.1 ms) than RTs to orientation targets (401.3 vs. 379.6 ms) [Note, though, that the RT difference between colour and orientation targets remained significant even with constant locations ($t(11) = 4.781$, $p = .001$).]

A separate ANVOA of the target-absent RTs, with the factors display (multiple items, single item) and target location (variable, constant), revealed the main effect of target location to be significant [$F(1,11) = 69.426$, $p < .001$]: target-absent RTs were 19.2 ms slower when the target location was variable rather than constant (415.1 vs. 395.9 ms). Although multiple-item displays were responded to somewhat slower than single-item displays (408.7 vs. 402.3 ms), the main effect of display was non-significant [$F(1,11) < 1$], nor was its interaction with target location [$F(1,11) < 1$].

Inter-trial effects. Feature- and dimension-based inter-trial transition effects were analyzed separately for the four conditions (MIv, MIc, SIv, SIc) by repeated-measures ANOVAs, each with the factors inter-trial transition (same dimension same feature, sDsF; same dimension different feature, sDdF; different dimension, dD) and dimension (colour, orientation). See Table 1 (left-hand side) for the results.

	Experiment 1a: within-subject			Experiment 1b: between-subject		
	sDsF	sDdF	dD	sDsF	sDdF	dD
MIv	359.9	361.0	374.3	387.0	392.8	415.4
MIc	336.2	344.0	365.2	365.7	376.5	407.1
SIv	374.0	383.4	413.8	386.1	398.5	432.7
SIc	349.8	366.5	401.7	358.2	375.7	410.6

Table 1: RTs (in milliseconds) as a function of inter-trial transition, separately for the four experimental conditions, in Experiments 1a and 1b (left-hand and right-hand side respectively); sDsF = same dimension, same feature; sDdF = same dimension, different feature; dD = different dimension; MIv = multiple items, variable location; MIc = multiple items, constant location; SIv = single item, variable location; SIc = single item constant location.

For all analyses, both main effects were significant. In all cases, RTs were faster to colour than to orientation targets [MIv: $F(1,11) = 24.367$, $p < .001$; MIc: $F(1,11) = 24.378$, $p < .001$; SIv: ($F(1,11) = 16.712$, $p = .002$; SIc: $F(1,11) = 8.069$, $p = .016$]. For conditions with variable target positions (MIv and SIv), but not those with constant target positions (MIc and Sic), the inter-trial effects were significantly influenced by target dimension [MIv: ($F(2,22) = 3.483$, $p = .049$; SIv: $F(2,22) = 4.396$, $p = .025$], due to a change to a colour target from an orientation target being somewhat easier than a change to an orientation target from a colour target.

In all cases though, the pattern of inter-trial effects was qualitatively similar between colour and orientation targets. The main effect of inter-trial transition was significant for all conditions [MIv: $F(2,22) = 12.680$, $p < .001$; MIc: $F(2,22) = 44.713$, $p < .001$; SIv: $F(2,22) = 62.904$, $p < .001$; SIc: $F(2,22) = 58.231$, $p < .001$]. Planned simple contrasts to follow up these effects in the various conditions showed that, in all conditions, there was a dimension-specific change effect: RTs were significantly slower when the target on trial *n* was defined in a different dimension to the target on trial *n*-1 [comparison dD vs. sDdF: MIv, $F(1,11) = 14.714$, $p = .003$; MIc, $F(1,11) = 33.420$, $p < .001$; SIv, $F(1,11) = 80.960$, $p < .001$; SIc, $F(1,11) = 46.738$, $p < .001$]. Although significant in all cases, the effect was smaller in multi-items conditions as compared to single item conditions [17.2 vs. 32.9 ms; $t(11) = 4.698$, two-tailed $p = .001$]; more precisely, 13.2, 21.2, 30.5, and 35.3 for the MIv, MIc, SIv, and SIc conditions, respectively]. However, the four conditions differed with respect to the occurrence of feature-specific change effects (within a repeated target-defining dimension): while these were significant for both single-item conditions [comparison sDdF vs. sDsF: SIv, $F(1,11) = 13.429$, $p = .004$; SIc, $F(1,11) = 20.557$, $p = .001$], for the multiple-items conditions, there was a significant effect only for the MIc condition [$F(1,11) = 19.986$, $p = .001$], but not for the MIv condition [$F(1,11) < 1$, n.s.]. Numerically, the effects were 1.2, 7.8, 9.4, and 16.7 ms for the MIv, MIc, SIv, and SIc

conditions, respectively, that is, overall, they were smaller for multi-items displays than for single-item displays [4.5 vs. 13.1 ms, $t(11)=-3.029$, two-tailed $p=.011$].

As the interpretation partially relies on the non-existence of feature-based inter-trial effects in the MIv condition, it is necessary to ensure that the power of the tests (contrast) performed to assess statistical significance of the difference between the SF and DF conditions was sufficiently high. Put differently, the argument requires guarding against falsely maintaining the null hypothesis. Test power (1-beta) was calculated using the post-hoc option of the G*Power program (Faul, Erdfelder, Lang & Buchner, 2007) under the assumption the test had the power to capture an effect of the order of magnitude observed in the three other experimental conditions (MIc, SIv, SIc); that is, an increase in RTs in a feature-change relative to a feature repetition trial of about 8 ms. If the power of the comparison used to test the significance in the MIc condition is sufficiently high to exclude false acceptance of the null hypothesis, it can be inferred that the same comparison in the MIv condition should have captured the significance of an effect of the magnitude observed in (e.g.) the MIc condition. The power analyses based on explained and residual variances revealed an effect size *f* as defined by Cohen (1988) of 1.35 and a power of .99 for the MIc condition; values for the SIv and SIc conditions were $f = 1.15$, power 1-beta = .99 and $f = 1.36$, 1-beta = .99. Thus, the power of the test comparing the SF and DF conditions was sufficient to detect an effect of a similar magnitude to those differences observed in the remaining conditions.

In a study designed to address contradictory findings of the effects of irrelevant singletons on visual-search performance, Leber and Egeth (2006) showed that observers do not switch to the most efficient strategy even if the task and the context would allow them to do so. Leber et al. induced observers to use either feature search mode (feature group) or singleton detection mode (singleton group) in a task in which either mode could be used to detect that target. By analyzing the effects of different types of distractor trials, they demonstrated that the feature group continued using the feature search, while the singleton group continued using the singleton search strategy on trials in which both strategies could be used. This result suggests that, contrary to the widely held assumption that observers always use the most efficient strategy available to perform a task, they tend to stick to the strategy that proved successful initially. With regard to the present study, two aspects of Leber and Egeth (2006) study are noteworthy: First, Leber et al. tested singleton vs. feature search, search modes that are likely to involve response selection mechanisms comparable with the response decision processes (based on saliency vs. template matching) assumed to underlie search in the present study. Second, Leber et al. (2006) presented only 24 practice trials to induce either of the two strategies, followed by 320 training trails in which the adopted strategy was consolidated. In the present experiments, observers performed three times this number of trials in an experimental condition, making strategy carry-over to other conditions (where the strategy acquired first would work) even more likely.

To examine whether the effects in the multiple-items conditions – in particular, the significant, albeit small feature-specific effect in the MIc condition – are due to carry-over of strategy (e.g., Leber & Egeth, 2006) from the single-item to the multiple-items conditions in those participants who performed the former condition first, 12 additional observers (seven female; age range 21 to 35 years, median age 25.8 years) were recruited. Six of these 12 additional observers performed only the multi-items conditions (MIv and MIc, in counterbalanced order) and six the single-item conditions (SIv and SIc). By combining their data with those for the starting condition of the original observers (of whom six had started with the multiple-items conditions and six with the single-item conditions), it became possible to compare the two display conditions between subjects, uncontaminated by any carry-over effects. See Table 1 (right-hand side) for the results.

As can be seen, the pattern of effects was very similar. More formally, the main effect of inter-trial transition was significant in for all conditions [MIv: $F(2,22) = 19.1968$, $p < .001$; MIc: $F(2,22) = 45.431$, $p < .001$; SIv: $F(2,22) = 68.313$, $p < .001$; SIc: $F(2,22) = 65.705$, $p < .001$]. Also, planned simple contrasts revealed the dimension change effect to be significant in all conditions [comparison dD vs. sDdF: MIv, $F(1,11) = 27.956$, $p < .001$; MIc, $F(1,11) = 48.389$, $p < .001$; SIv, $F(1,11) = 64.727$, $p < .005$; SIc, $F(1,11) = 67.315$, $p < .001$] numerically, the effects were 22.6, 30.6, 34.2, and 34.9 ms for the MIv, MIc, SIv, and SIc conditions, respectively]. Furthermore, while again there were significant feature-specific change effects (from one target-defining feature to another within the same dimension) for the single-item conditions [comparison sDdF vs. sDsF: SIv, $F(1,11) = 19.348$, $p = .001$; SIc, $F(1,11) = 21.759$, $p = .001$], for the multiple-items conditions, there was such an effect only with constant, central target location [MIc: $F(1,11) = 15.336$, $p = .002$], but not with variable target location [MIv: $F(1,11) = 3.626$, n.s.]. Numerically, the effects were 5.8, 10.7, 12.4, and 17.5 ms for the MIv, MIc, SIv, and SIc conditions, respectively. This replicates the findings of the within-subject analysis, and shows that the (significant) feature-specific effect in the MIc condition is not simply due to carry-over of decision strategy from the single- to the multi-item(s) conditions.

Discussion

Reaction Times. Overall, target-present RTs were faster with multi-items displays than with single-item displays (despite a higher false-alarm rate, suggesting a tendency to respond target-present, in the single-item conditions). While this fits with the view that target detection in multiple-items conditions is based on fast, saliency-based mechanisms, it is difficult to square with the idea that this type of task involves a time-consuming (pre-selective) search component in addition to the (post-selective) decision component that it shares with the single-item conditions.

Furthermore, the finding that, in the single-item conditions (but not the multiple items conditions), target-present RTs are statistically as slow as target-absent RTs suggests that responding to a single-item display, whether it contains a target or a distractor, is based on the same process, which is highly

likely to involve access to the featural level, that is: identification of the single-item features and comparison against a target (or distractor) template. This process of feature analysis is relatively slow: it consumes time over and above that required with multiple-items displays to establish target-presence – that is, to detect the presence of a pop-out, or saliency, signal. With multiple-items displays, a target-absent response is likely to be given as a default response unless a saliency signal emerges within a certain amount of sampling time (in which case a target-present response is triggered; Chun & Wolfe, 1996). This would explain why target-absent decisions take longer than target-present decisions with multi-items displays. In any case, it appears that the addition of multiple non-target items to display changed the nature of the task (even when the target location was perfectly predictable), from feature discrimination to singleton detection.

Also worthy of note is that the factor target location (constant vs. variable) did not interact with display (single item vs. multiple items). This implies that, whatever the type of display, variable location added a constant amount of time – presumably required to localize the target and direct focal attention to it – to decision making and responding on a trial. [This does not mean that focal-attentional stimulus analysis is strictly necessary in the multi-items, particularly the MIv, conditions; rather, as argued by Müller and Krummenacher (2006), the same signal that triggers a spatial orienting response to the target may also be used to initiate a detection response. See also Töllner, Zehetleitner, Gramann and Müller (2010) in chapter 5.]

RTs to colour targets were somewhat less affected by variability, as compared to constancy, of target location than RTs to orientation targets, suggesting that colour targets were somewhat more potent in summoning and/or engaging focal attention than orientation targets.

Inter-trial Effects. The inter-trial effects were overall smaller under MI conditions than under SI conditions. This alone would argue against the same decision mechanism (generating inter-trial effects) being involved in both types of task. In particular, as predicted, there was no (significant) feature-specific effect in the MIv condition (only a dimension-specific effect), suggesting that this task is solved via response decisions being (largely) based on the detection of an above-threshold supra-dimensional saliency signal. By contrast, there are feature-specific effects, in addition to dimension-specific effects, in the single-item conditions, indicating that (post-selective) feature analysis is required to solve the task with only a single item in the display. The pattern of effects suggests that the features of the single item presented are serially compared with a set of (target) memory templates, where comparisons within the same dimension (as that which was target-defining on the preceding trial) are given priority over comparisons involving a dimensional change in the template. This would explain why there are dimension-specific change effects over and above feature-specific effects.

On a serial model, where, following an unsuccessful match with an intra-dimension template, one of the two templates in the other dimensions is selected first for the comparison and only then, in case of a further mismatch, the other template in the changed dimension, one would expect the dimension-

specific effect to be, on average, 1.5 times the size of feature-specific effect in single-item conditions., However, the dimension-specific effect is actually even larger, that is, about 2 times the feature-specific effect (2.2 [Experiment 1a] to 2.3 [Experiment 1b] times). This would suggest that either all alternative features in the changed dimension are checked exhaustively, or that there is an additional time overhead for loading the templates for the changed dimension into working memory. Of further interest in this context is that, in single-item conditions, target-absent RTs were as fast as target-present RTs in the dD condition, 402.3 versus 407.8 ms ($t(11)=1.031$, n.s.) (whereas they were much slower in multi-items conditions, 408.7 vs. 369.7 ms, $t(11)=5.943$, 2-tailed $p < .001$). This could mean that, if the second comparison in the changed dimension provides a mismatch, a negative decision is made as rapidly as the positive decision if this comparison provides a match (consistent with exhaustive checking).

Interestingly, observers appear to be using such a strategy of matching stimulus features against target templates, even though a theoretically more efficient alternative would be to compare the stimulus presented against the distractor template. In such a scheme, the stimulus must be a distractor if neither a colour nor an orientation check provides a mismatch, in which case a negative decision can be made; and it must be a target, requiring a positive decision if one comparison provides a mismatch, which statistically would require 1.5 checks. Accordingly, target-present responses should be faster than -absent responses – an effect that was not significant in Experiment 1; furthermore, assuming that checking on trial *n* starts with the dimension checked last on trial *n-1*, there should be a dimension-specific inter-trial effect, but no feature-specific effect – which is also at variance with the findings. Thus, it appears that observers use a confirmatory strategy, rather than a dis-confirmatory one, perhaps because focally attended stimuli are automatically processed for feature identity.

Furthermore, while there are significant feature-specific effects in both SI conditions, under MI conditions, such effects are overall smaller and significant only with targets appearing consistently in the display centre. The feature-specific effect in the latter condition (MIc) would appear to be inconsistent with the notion that in multi-item conditions, responding is generally based on (overall-) saliency signals. Note, however, that RTs are overall faster in the MIc condition compared to the SIc condition (381.2 vs. 388.6 ms), despite the fact that no search was necessary in either condition because focal attention could be deployed to the (invariable) target location in both conditions. [Interestingly also, target-absent RTs were still slower than dD target-present RTs in the MIc condition (400.1 vs. 365.2 ms), whereas they were equally fast in the SIc condition, which suggests a difference in the decision process between the two conditions.] This difference is difficult to account for by the mechanisms envisaged by Mortier et al. (2005), unless one admits that response decisions are influenced (expedited) by some second source of information not available in the SIc condition, namely: a fast-operating (pre-attentive) saliency-based target individuation process, in addition to a slower-operating (focal-attentional) target discrimination process. Although the latter process was not

strictly necessary to perform the task, it appears that observers engage in it to some extent (the inter-trial effects appeared less marked in the MIc condition compared to the SIc condition), even if they had not performed any SI conditions beforehand (a feature-specific effect in the MIc condition was obtained in the between-subject Experiment 1b, as well as the within-subject Experiment 1a). One possible account for this may be derived from the 'perceptual-load theory' proposed by Lavie and her colleagues (e.g., Lavie, 1995, 2005). In the MIc condition, focal attention can be allocated in advance to the fixed, central target location. Consequently, the central display element is processed attentionally as soon as it appears, involving an (automatic) element of feature analysis (even though this is would not be necessary to perform the task). This outcome of this feature analysis process would to some extent influence the response decision, which is, however, mainly based on the (fast) saliency-based target individuation process that operates in parallel. This would give rise not only to a feature-specific inter-trial effect in the MIc condition, but also (relative to the MIv condition) enhanced feature- and dimension-based inter-trial effects – because a post-selective source of inter-trial effects would add to a pre-attentive source. This second source plays no role in the MIv condition, in which there is very little analysis of target features following selection (see also Töllner et al., 2010).

In summary, the pattern of general RT and inter-trial effects revealed in Experiment 1 suggests a fundamental difference in the way the task is solved with multi-items displays (where responses are largely saliency-based and – dimension-specific – inter-trial effects arise from a pre-selective coding stage) and single-item displays (where responses involve focal-attentional feature analysis, producing feature-specific inter-trial effects) and that therefore the conclusions out of Mortier et al.'s (2005) are not tenable. Further evidence for this was found in Experiment 2 (see next chapter 4.2).

Alternative accounts

Some other attempts to explain previous-trial effects were made by Huang, Holcombe and Pashler (2004) or Hillstrom (2000) for example. In both accounts PTE are explained by task-relevant episodic retrieval. Three stages of target detection are proposed: on the first stage of target detection the target has to be searched, on the second, it is decided, whether a candidate item in fact is the target and on the final stage the response is selected and executed (Huang et al., 2004). According to Huang et al., the second stage involves episodic memory of similar stimuli and responses from earlier trials. In case, the target is repeated, the response is automatically retrieved, in case the target is changed the new target definition interferes with the decisional stage in which the selected item is recognised as the target, the current response is delayed and a new one is programmed. According to Huang et al. inter-trial effects arise at a stage on which the target is already selected, in other words, at a decisional stage. Hillstrom (2000) on the other hand hypothesised episodic retrieval to take place at the first stage of the detection mode. She assumes that the retrieved memory about past trial episodes is used to reactivate the attentional preferential setting in order to detect the target faster.

By closer examination it seems, that the models including episodic memory retrieval can be subsumed under either perceptually or response-based accounts. Whereas Huang et al.'s (2004) hypothesis can be placed at the response-related end of the processing stream, Hillstrom's (2000) are rather placed at the perceptual end.

A third account that has to be mentioned at this point is the ambiguity resolution account (Olivers & Meeter, 2006, see also Meeter & Olivers, 2006) which claims that the larger the ambiguity of a search display, say, the less salient a particular target is (due to a high target-distractor similarity), the more pronounced are the previous-trial effects. Olivers and Meeter (2006) hypothesised that "the present/absent task is more ambiguous than the compound task, because the response decision is based on uncertain perceptual evidence. In contrast, the compound task can only be fulfilled when the perceptual evidence has been disambiguated, with no direct relationship between the response decision and target presence." (p. 23). In a series of experiments using present/absent, as well as Go/Nogo and compound (and compound/absent) tasks Olivers and Meeter finally succeeded in finding robust inter-trial effects in a compound task using more ambiguous stimulus material (an irrelevant singleton on compound absent trials, in order to enlarge confusion as to the correct answer).

In contrast to the assumptions of Olivers and Meeter (2006), Töllner et al. (2008) found conventional inter-trial effects on a behavioural level as predicted by Müller and Krummenacher (2006) in response-repetition inter-trial transitions under conditions of low target ambiguity (high target saliency) in compound search. Under the same conditions, ERP-wise inter-trial effects were even reflected for both, response-repetition and -change inter-trial transitions (as reported above).

4.2 The redundant signals effect

In addition to the relevant findings on previous-trial effects (e.g. Found & Müller, 1996; Gramann et al., 2007; Müller & Krummenacher, 2006; Töllner et al., 2008), further evidence for an early pre-attentive locus of dimensional weighting effects (and, consequently, the existence of top-down modulation of the early processing stage) was provided by Krummenacher et al. (2001, 2002), who introduced the 'redundant signals effect' (RSE) into visual search for singleton feature targets. Usually, if the redundant signals paradigm is employed, participants perform a Go/No-go task with two different Go conditions (e.g. Mordkoff & Yantis, 1991, 1993). In the studies of Mordkoff et al., in one of the two conditions, the single-target condition, one target appeared in the display; in the second, the dual (redundant) target condition, two targets were presented simultaneously. The latter condition is referred to as the 'redundant signals' condition because the experimental display is 'over-defined' relative to the information required to perform the task; that is, the display contains two (rather than the one required) task-relevant target signals. RTs in the redundant target condition were found to be expedited compared to the single target condition, revealing a RT 'redundancy gain' or a 'redundant signals effect' (RSE; Mordkoff & Yantis, 1991).
Krummenacher et al. (2001) adapted the original paradigm to visual search tasks in such a way that they did not present two individual targets simultaneously (i.e., two signals at different locations), rather, they added a second dimensional signal by defining the target item on the colour and orientation dimension (i.e., two signals at the same location). In their visual search task, a singly defined feature singleton target was presented among green square-shaped distractors, differing from distractors either by colour (a red or turquoise square) or orientation (a green diamond), whereas redundantly defined singleton targets differed from distractors in colour and orientation (a red or turquoise diamond). Krummenacher et al. (2001) introduced this manipulation in order to be able to test redundant targets under cross-dimensional search conditions. Krummenacher et al. (2001) found RT redundancy gains: redundantly defined targets (differing from distractors in two dimensions) were detected significantly faster than singly defined targets (differing from distractors by colour or orientation only).

Parallel versus parallel co-active integration of dimension-based signals

Two theoretical models can account for the redundant signals effect; parallel (separate) activation of the response execution module versus co-active activation of the response (Miller, 1982). Separate-activation models claim that redundant signals are processed either serially (one signal after the other in a single processing channel) or they enter a parallel race in which the faster of the two signals processed in two independent channels triggers the response. Serial processing can be ruled out. In the case of a parallel race, mean RTs to redundant signals should be faster than RTs to single signals, simply because the probability that one out of two signals is detected at a given point in time (relative

to display onset) is higher than a single signal is detected at the that same point in time (statistical facilitation, e.g. Raab, 1962). However, with regard to the entire distribution of RTs, multi-channel parallel race models are limited in such a way that redundant signal RTs cannot be faster than the fastest RT to any of the single signals. In the case of the visual search task of Krummenacher et al. (2001) the prediction of parallel race models implies that RTs to redundant targets defined in the colour and orientation dimensions [C&O] must not be faster than the fastest RT to the singly defined colour [C] or orientation [O] targets for the assumption of a parallel race model to hold.

Miller (1982) proposed a test to differentiate between parallel race models and cases in which the prediction of the race model is violated: the 'race model inequality' (RMI). The RMI states that for the assumption that separate signals activate the response module to hold, the probability of having responded to a redundantly defined target at a given point in time *t* after display onset [$P(RT < t \mid \text{C\&O})$] must be smaller or equal to the probability of having responded to a colour target at time *t* [$P(RT < t \mid \text{C})$] plus the probability of having responded to an orientation target at time *t* [$P(RT < t \mid \text{O})$].

Formally, the RMI applied to the above example is:

$$P(RT < t \mid \text{C\&O}) \leq P(RT < t \mid \text{C}) + P(RT < t \mid \text{O}).$$

In general terms, the RMI is:

$$P(RT < t \mid T_1\&T_2) \leq P(RT < t \mid T_1) + P(RT < t \mid T_2),$$

where *t* is the time since display onset and T_1 and T_2 are targets 1 and 2.

If the RMI is violated [i.e. if $P(RT < t \mid \text{C\&O}) > P(RT < t \mid \text{C}) + P(RT < t \mid \text{O})$], or, in words, if the fastest RTs to redundant targets are found to be faster than the fastest RTs to single targets, the assumption of independent separate channel race models is rejected. In other words, violations of the RMI provide evidence for parallel co-active activation models underlying processing of redundant targets. Co-active activation models claim that redundant signals are processed in parallel, but rather then entering a race to activation a subsequent response generation component, they jointly contribute to the activation of subsequent response module. In other words, the two questions addressed are i) whether redundantly defined targets expedite RTs relative to non-redundant targets and b) in the case of faster redundant-target RTs, whether the redundancy gains are due to a parallel race of signals or to coactive integration of signals. The question is of great theoretical interest as it contributes to the issue of whether signals coding different dimension-based signals are integrated before focal attention is allocated and, therefore, before responses are triggered.

Visual search for dimensionally redundant feature singletons

Krummenacher et al. (2001) showed that dimensionally redundant targets are responded to faster compared to dimensionally singly defined targets. The finding of mean RT redundancy gains is not sufficient, however, to discriminate whether the response is triggered by a parallel race of signals or by a co-actively activated response module (in target-present trials). Using Miller's (1982) race model

inequality, Krummenacher et al. showed that redundant signals violated the assumption of a parallel race; these violations provide evidence of co-active activation of a module that triggers the response. In terms of Müller et al.'s (1995, Krummenacher & Müller, 2005) dimension weighting model, faster RTs to redundantly defined targets are based on an integrated saliency representation of the two target dimensions: the two relevant dimension-based saliency signals are not processed independently of each other up to the stage of response generation, rather they co-actively contribute to the summed overall saliency activation that controls the allocation of the focal spotlight of attention (Wolfe, 1994).

Further, in their experiments, Krummenacher et al. (2001) provided evidence that the integration of dimensionally redundant target signals is modulated by previous-trial effects. In cross-dimensional search, previous-trial effects of the following pattern were observed: Repetition of colour, orientation or redundant targets across trials always expedited RTs for the second relative to the first of two consecutive trials. Krummenacher et al. (2001) also observed that in cross-dimensional, in contrast to within-dimensional search (i.e., search for a target defined in the same dimension in a given block of trials), no violations of the RMI occurred. They argued that the lack of coactive processing was due to the inter-trial variability of dimension-based target definitions and the requirement to shift processing resources between dimension-based modules. To test this assumption, they analysed pairs of target repetition trials and found no violations of the RMI when they compared RTs to the first of two consecutive redundant targets (*R*R) to RTs to the first of two consecutive single targets (*C*C and *O*O). However, when they compared RTs to the second of two consecutive redundant targets (R*R*) with RTs to the second of two consecutive single targets (C*C* and O*O*) there were significant violations of the RMI. According to the DW account (Müller et al., 1995, 1996; Krummenacher et al., 2005) the first of the two consecutive (redundant) targets adjusts the dimensional weights for further processing; therefore, the integration of dimension-based signals in the second of two consecutive trials is based on an optimised distribution of processing weights, rather than an equal distribution of resources to the relevant dimensions as in the first of the two trials.
Krummenacher et al. (2001) showed, that dimensional signals are processed in a co-active fashion at a pre-attentive stage of processing, at signal summation onto the priority map, but that the co-activation is modulated by dimension-specific inter-trial modulations of processing resources. Inter-trial RT modulations arise at a pre-attentive level; consequently, the modulation of RTs (relatively expedited RTs to targets defined on the same dimension across two trials and relatively slowed down RTs when the target dimension changed across trials) reflects a top-down modulation at the level of pre-attentive processing stages. The assumption of a preattentive locus of inter-trial effects and the susceptibility of early processing stages to top-down modulation was challenged recently, however, by a number of studies using a variety of perceptual tasks. Taken together, these studies suggest that inter-trial effects and redundancy gains arise at later, post-selective, stages of processing at the level of response selection or execution.

According to one of the accounts challenging dimension weighting, the Cohen's 'dimension action' (DA) account (Cohen & Shoup, 1997, 2000) multiple response decisions can be programmed simultaneously and the role of attention is to ensure that only one of the decisions is executed. In other words, attention is required to gate information to response-execution centres. In a number of experiments, Feintuch and Cohen (2002) presented their observers with redundant signals either at one (one redundantly defined target) or two locations (two singly defined targets presented simultaneously). The DA model makes clear predictions concerning the conditions in which more than one relevant signal is presented in the visual field: "When attention is focused on one target, only one selected response (from the target on which attention is focused) will be transferred to the executive functions; when attention is focused on both targets, both selected responses will be transferred to the executive functions." (Feintuch & Cohen, 2002, p. 361). In line with their assumption, they found co-activation of the dimensional signals to occur only when the redundant signal was presented at one location, in contrast, when the signals were presented at two positions, no violations of the RMI were obtained (Experiment 1). There was one notable exception, however: when the two separate signals were presented within the focus of attention (Experiment 2), then, again, co-activation was found.

However, in a subsequent study, Krummenacher et al. (2002, Experiments 1 and 2) first compared mean RT redundancy gains and violations of the RMI for single targets redundantly defined in two dimensions and dual redundant targets, each defined in a different dimension and presented at different display locations simultaneously. For both types of redundant displays mean RT redundancy gains and violations of the RMI were found (in line with DW and DA), however, mean redundancy gains were reduced in the dual redundant target compared to the single redundant target condition. The latter finding is in line with the DW account (Müller et al., 1996) that predicts location-specific overall-saliency units to show a higher amount of activation if two signals are presented at the same location compared to different locations. The finding is in contradiction to the DA model (Cohen & Shoup, 1997, 2000) that predicts that response selection units are activated no matter whether the redundant signals are presented at one or two locations and no matter at which location, either. The activation of a dimensional response unit would simply indicate the presence of an odd-one-out stimulus in the corresponding dimension. (The response units operate in an all-or-nothing fashion.) But when presenting dual redundant targets, RMI violations are observed only when the redundant target signals are spatially coincident or relatively close (but not when they are distant) – consistent with the hypothesis of saliency models that assume that overall-saliency map units integrate the incoming information in a spatially scaled manner. Furthermore, with dual targets (presented at separate, but nearby locations), violations of the RMI are observed only if the critical target features are defined in different dimensions (but not when they are defined within the same dimension) – consistent with theories of saliency computation that assume that the saliency map integrates dimension-specific feature contrast signals.

Finally, Krummenacher et al. (2002, Experiment 3) presented observers with a dimensionally redundant singleton target which appeared (with a probability of 80%) at a symbolically (arrow cue) pre-cued quadrant or (with a probability of 20%) at an un-cued quadrant of the display. Target detection was boosted within cued quadrants (significant effect of cue) and, more importantly, dimensionally redundant signals were found to be processed in a co-active fashion in un-cued as well as cued display regions, that is, violations of the RMI were found independent of the (cued or un-cued) target location; consequently, co-active processing of dimensional signals is independent of whether the signals are under the focus of attention or not. These results suggest that the integration of dimensionally redundant target signals occurs independently of and prior to the allocation of spatial attention. This is in contrast to the findings of Feintuch and Cohen (2002) who claimed that attention plays a critical role in the integration of response unit activity of separate dimensions.

Using the redundant signals effect, it is also possible to address Mortier et al.'s (2005) challenge of DW that is based on the finding of inter-trial effects in single-item (non-search) tasks.

Experiment 2: Redundant signals effects in visual search and discrimination tasks: separable pre-attentive and post-selective effects

Purpose of the present study

Experiment 2 was designed to examine another prediction deriving from the account of Mortier et al. (2005) with respect to the redundant signals effect by comparing processing of targets differing from distractors on one (colour or orientation, single targets) or on two dimensions (colour and orientation, dual [redundant] targets) between multiple- and single-item(s) conditions. Using redundantly defined targets allows for the identification of the mechanism (serial, parallel race, parallel co-active) underlying the processing of redundant dimensional target signals (Miller, 1982; Krummenacher et al. 2001, 2002; Zehetleitner, Krummenacher & Müller, 2009).

The results of Experiment 1 suggest that, in the multiple-item condition, responses are based more or less directly on an overall-saliency representation of the display. The location-specific integration mechanisms in the overall-saliency map integrate dimension-specific feature contrast signals in a weighted manner – giving rise to a pattern of dimension-specific, but not feature-specific inter-trial effects. Krummenacher and colleagues (2001, 2002) have shown that, in singleton feature search, RTs to targets redundantly defined in two dimensions are faster than RTs to targets defined in just one dimension and that these RT gains can be understood as being generated in a parallel co-active processing mechanism. By finding violations of the RMI, Krummenacher et al. (2001, 2002) concluded that redundant target signals are integrated at some processing stage that drives (in a co-active fashion) the required target detection response. Krummenacher et al. (2001, 2002) identified the

integration stage, in singleton feature search, with the (pre-selective) overall-saliency map, rather than some, post-selective, stimulus analysis or stimulus-to-response mapping stage. On the basis of this interpretation, co-activation effects by dimensionally redundant singleton feature targets were expected in the multi-item condition of Experiment 2 (reflecting signal integration at a pre-selective processing stage).
By contrast, with regard to the single-item condition, the results of Experiment 1 suggest that making a response decision requires access to the feature level in a post-selective (analysis) process. That is, the target attributes are compared in a serial fashion to the templates of possible targets held in working memory. Comparison starts with the feature template that provided a match on the preceding trial; if there is no match with the current target, the next comparison will be with the alternative feature template within the same dimension, and only if there is no match again, comparisons with the templates in the other dimension are initiated. The suggested sequence of target-to-template matches is expected to give rise to a pattern of dimension-specific as well as feature-specific inter-trial effects.

The critical question is whether effects of coactive processing (as demonstrated with multi-item displays) would also be found in single-item conditions, when the single target exhibits two response-critical features in two dimensions (e.g., being both red and right-tilted), compared to just one (e.g., the feature red alone or right-tilted alone, each of which requires a target-present response). With single-item displays the pre-selective coding stages contribute little to responding (because perceptually, the single target item is – by virtue of being the only display item – always defined in multiple dimensions). Thus, the question is whether two post-selectively analyzed target features (that are to be discriminated from non-target features) can simultaneously activate the target-present response; restated, whether multiple features can be compared simultaneously with the target description held in working memory. If not – that is, if there is co-activation only in multi-item but not single-item displays) – , then this would lend further support to the assumption that the critical processing stages in the non-search (discrimination) task of Mortier et al. (2005) and the singleton feature search (detection) tasks examined by Müller et al. and Krummenacher et al. are different. Although there are studies that have reported co-activation effects in discrimination tasks (e.g., Mordkoff & Yantis, 1993), it is not a-priori clear whether these findings would extend to the non-search task of Mortier et al. (2005). For these the results of Experiment 1 suggest that it involves a post-selective comparison process that checks only one feature at a time. If it is indeed not possible to compare multiple (dimensional) features simultaneously with the target description(s) held in working memory (as also predicted by Huang & Pashler's, 2007, Boolean map theory, BMT), then no co-activation effect would be expected when the single display item (in the non-search task) possesses two target-defining features (in separate dimensions).

The assumption that processing of dimensionally redundant target signals in single-item conditions operates serially, rather than in a parallel or parallel-coactive fashion, can be tested by examining the RT distributions for violations of the so-called Grice inequality (Grice, Canham & Gwynne, 1984; see also Townsend & Nozawa, 1995; Van Zandt, 2002) The Grice inequality (which is closely related to the RMI) states that, if redundant signals are processed in a parallel-race architecture, the larger of the two probabilities of having responded to a dimensionally singly defined target at a given time *t* after display onset [$\max\{P(RT < t \mid \mathrm{C}), P(RT < t \mid \mathrm{O})\}$] must be smaller or equal to the probability of having responded to a redundant target at time *t* [$P(RT < t \mid \mathrm{C\&O})$].
Formally, the Grice inequality is: $\max\{P(RT < t \mid \mathrm{C}), P(RT < t \mid \mathrm{O})\} \leq P(RT < t \mid \mathrm{C\&O})$.
Violations of this inequality [i.e., $\max\{P(RT < t \mid \mathrm{C}), P(RT < t \mid \mathrm{O})\} > P(RT < t \mid \mathrm{C\&O})$] rule out parallel-race models and provide evidence for serial processing of dimensional signals. Therefore, if processing of redundant targets in the single-item conditions of Experiment 2 requires serial comparisons with target templates in working memory, violations of the Grice inequality would be expected – rather than violations of the RMI, which, according to Krummenacher et al. (2001, 2202) would reflect signal integration at an early processing stage in cross-dimensional singleton search. Conversely, in multiple-items conditions, violations of the RMI, but no violations of the Grice inequality are expected. Finding such a double dissociation would provide strong evidence that the underling processes are different in multiple-items search tasks and single-item non-search tasks (parallel co-active processing in multiple-items conditions vs. serial processing in single-item trials), so that the two types of task cannot be directly compared.

Overview of Experiment 2

To test for such a double dissociation between (multiple-item) search and (single-item) non-search tasks, observers in Experiment 2 were presented with either multi-item or single-item displays, with targets either defined singly in one dimension or redundantly in two dimensions, and asked to indicate whether the display contained a target item (target-present response) or (a) distractor item(s) (target-absent response). As in Experiment 1, distractors were vertical green bars, targets were vertical red or blue bars, left- or right-tilted green bars (single targets), and different from Experiment 1, red or blue bars tilted to the left- or the right (redundant targets).
Note that only variable-location conditions (MIv and SIv) were tested in Experiment 2. The reason for examining for serial processing in the SI condition derives from Huang and Pashler's (2007) Boolean map theory (BMT), according to which the generation of conscious visual representations – which are hypothesized to be necessary for the decision whether a single item is a target or a non-target – requires that visual features are indexed by location. Presentation of targets at variable, rather than constant, positions in the SI condition would force this indexing of features by location, while also making this condition more similar to the multiple-item conditions.

Further, as it was assumed that the strategy that observers had to adopt to solve the SI condition (performed first) would be carried to the MI condition (performed second), even though the latter condition would allow for a different, saliency-based strategy. To examine for such strategy carry-over effects, half of the observers completed the MI condition followed by the SI condition, and vice versa for the other half.

Method

Participants. Twenty-four observers (twelve female; age range 20 to 29 years, median age 23.4 years) participated in Experiment 2. All had normal or corrected to normal vision, all reported normal colour vision, and all were right-handed. Participants were paid at a rate of CHF 10 (approximately $ 9) per hour or received course credits. Four of the observers had participated in Experiment 1. All observers were naïve as to the purpose of the experiment; the majority of them had no previous experience with visual search task.

Apparatus, stimuli, task. The apparatus was the same as in Experiment 1. Stimuli were also the same as in Experiment 1, except that, in addition to targets defined in one dimension (i.e., in either colour or orientation) only (singly defined targets), there were also targets defined in two dimensions (i.e., in both colour and orientation; redundant targets). Distractors were vertical green bars. Singly defined colour targets were red or blue vertical bars, and singly defined orientation targets were left- or right-tilted green bars. Redundant targets differed from distractors in two dimensions: they were red and left-tilted, red and right-tilted, blue and left-tilted, or blue and right-tilted.

Procedure and timing. Procedure and timing were the same as in Experiment 1. However, only the multiple-item variable target location (MI) and the single-item variable target location (SI) conditions were tested in Experiment 2. The sequence of conditions was counterbalanced across participants: Half of the observers started with the multiple-item condition, the other half with the single-item condition.

Each of the two conditions comprised of 960 trials, completed in two sessions of five blocks of 96 trials. There were s total of 576 target-present and 384 target-absent trials (ratio of 60% to 40%). Each of the eight possible target types (4 singly and 4 redundantly defined targets) were presented with the same probability, in randomized order. Prior to each experimental condition, observers completed one block of 96 practice trials to become familiar with the task. One session took about 30 min to complete; the two sessions of the experiment were run on two consecutive days.

Results

RTs faster than 200 ms and slower than 1000 ms were excluded from analysis (0.36% of all trials) as anticipations or exceedingly slow reactions. Additionally, RTs exceeding mean RT by more than three standard deviations were excluded from analysis, separately for each participant and each of the two conditions (less than 1.3% of all trials). As the focus of Experiment 2 was on redundancy gain effects,

only these results, along with an analysis of the inter-trial effects, will be reported. All other effects were generally similar to Experiment 1, as far as the two experiments are comparable design-wise.

Inter-trial effects. Importantly, the inter-trial effects (transitions between trials with singly defined targets) replicated the pattern observed in Experiment 1. In the MI condition, mean RTs were 396.3, 395.5, and 416.5 ms for sDsF, sDdF, and dD trials, respectively [main effect of inter-trial transition, $F(2,46) = 7.381$, $p < .002$]; that is, there was no significant cost for a feature change within a repeated dimension [sDsF vs. sDdF, -0.9 ms, $F(1,23) < 1$, n.s.], while there was a cost for changing the dimension [sDdF vs. dD, 21.1 ms, $F(1,23) = 13.017$, p = .002].

By contrast, in the SI condition, RTs were 384.1, 397.8, and 430.6 ms for sDsF, sDdF, and dD trials, respectively [$F(2,46) = 36.620$, $p < .001$]; that is, there was a significant feature-change effect [sDsF vs. sDdF, 13.7 ms, $F(1,23) = 6.997$, $p = .028$] as well as a significant dimension change effect [sDdF vs. dD, 32.8 ms, $F(1,23) = 45.496$, $p < .001$].

In line with Experiment 1, this pattern of feature-specific effects, in addition to a dimensional effect in the SI, but not the MI, condition suggests that decision making involves serial feature checking in single-item, but not multiple-items conditions.

Further analyses of the inter-trial effects separately for observers who performed the MI condition first and the SI condition second, and vice versa, revealed the effect to be significant in all conditions, with the exception of MI 2nd [MI 1st: $F(2,22) = 10.906$, $p = .001$; MI 2nd: $F(2,22) = 0.904$, $p = .420$; SI 1st: $F(2,22) = 16.422$, $p < .001$, SI 2nd: $F(2,22) = 20.362$, $p < .001$]. While there was no differential order-of-performance effect between the SI condition (SI 1st: 384.9, 396.9, and 434.1 ms for sDsF, sDdF, and dD transitions, respectively; SI 2nd: 383.3, 398.7, and 427.1 ms), for the MI conditions, the inter-trial, in particular the dimension change, effects were less robust for observers who had performed the SI condition first (400.6, 405.1, and 412.6 ms for sDsF, sDdF, and dD transitions, respectively) than for observers who had started with the MI condition (MI 1st 392.1, 385.8, and 420.4 ms).

Mean RT redundancy gains. Mean RTs of the three types of target-present trials were examined, separately for the MI and SI conditions, by one-way repeated-measures ANOVAs with the factor target type (single colour, single orientation, redundant colour plus orientation). The target type effect was significant for both experimental conditions [MI: $F(2,46) = 81.240$; SI $F(2,46) = 84.454$; both ps $< .001$]. In particular, mean RTs to redundant targets were faster than those to single orientation and colour targets, in both conditions (see below). This pattern was unaffected by whether observers had performed the MI condition first and the SI condition second, or vice versa: MI 1st: $F(2,22) = 49.713$; MI 2nd: $F(2,22) = 32.673$; SI 1st: $F(2,22) = 38.772$; SI 2nd: $F(2,22) = 61.742$; all ps $< .001$.

Table 2 presents the mean RTs for singly defined colour and orientation targets and redundantly defined colour plus orientation targets. Also shown are the mean RT redundancy gains relative to the faster of the two singly defined dimensions (Miller & Lopes, 1988) as well as the F-values of the corresponding, planned comparisons. As can be seen, the RTs to redundant targets were significantly

faster than those to the fastest singly-defined targets in both experimental conditions of Experiment 2. However, while there are significant mean RT redundancy gains in all conditions, the present analysis (mean RT) leaves it open how these gains were generated, whether by a parallel race of the two target-defining dimensions, by coactive integration of the two redundant-target signals (as expected for MI conditions), or by serial checking of the two possible target-defining dimensions (as expected for SI conditions). Note that even serial checking would predict a mean RT redundancy gain because, with redundantly defined targets, a target signal is found 'immediately', whatever dimension is checked first; by contrast, with singly defined targets, finding a target-signal would require 1.5 dimensional checks, on average.

	RT [ms]			Gain*			
Condition	Col	Ori	Col&Ori	[ms]	$F_{(1,23)}$	$F_{(1,11)}$	p
MI	397.3	430.1	384.8	12.5	28.594		<.001
MI-1st	392.6	430.2	380.9	11.7		30.097	<.001
MI-2nd	402.0	430.0	388.8	13.3		9.683	=.010
SI	392.9	437.2	381.2	11.8	24.770		<.001
SI-1st	398.3	438.2	387.1	11.2		7.319	=.020
SI-2nd	387.5	436.1	375.2	12.3		24.598	<.001

* Gain relative to the faster single target condition.

Table 2: Mean RTs (in milliseconds) for singly defined colour and orientation targets and redundantly defined colour plus orientation targets. Also shown are the mean RT redundancy gains relative to the faster of the two singly defined dimensions (Miller & Lopes, 1988), as well as the F-values of the corresponding, planned comparisons.

RT distribution analyses – race model inequality. To examine how the mean RT redundancy gains are generated in the two conditions of Experiment 2, the distribution of redundant-target RTs, as compared to the single-target RTs, was tested for violations of Miller's (1982) race model inequality, $P(RT < t \mid \mathrm{CO}) \leq P(RT < t \mid \mathrm{C}) + P(RT < t \mid \mathrm{O})$, separately for the MI and SI conditions, for the entire sample of 24 observers. As can be seen from Table 3, the distribution analyses did not reveal any significant violations of the RMI in either of the two conditions. Note, however, that $P(RT < t \mid \mathrm{CO})$ did not differ significantly from $P(RT < t \mid \mathrm{C}) + P(RT < t \mid \mathrm{O})$ for the first three quantiles of the RT distributions in the MI condition; by contrast, $P(RT < t \mid \mathrm{CO})$ was significantly smaller than $P(RT < t \mid \mathrm{C}) + P(RT < t \mid \mathrm{O})$ already at the first three quantiles in the SI condition. That is, performance in the SI condition was further away from violations of the RMI than performance in the MI condition.

a) MI (N=24)

			Race inequality			Grice inequality		
q	p_c	p_o	p_c+p_o	t(23)	p	$\max(p_c,p_o)$	t(23)	p
5	4.09	1.58	5.66	-0.900	.189	4.26	1.382	.090
10	7.97	3.24	11.20	-1.176	.126	7.97	2.829	.005
15	11.45	5.35	16.80	-1.586	.063	11.46	4.683	.000
20	16.02	7.90	23.92	-3.327	.001	16.08	4.901	.000
…								

b) SI (N=24)

			Race inequality			Grice inequality		
q	p_c	p_o	p_c+p_o	t(23)	p	$\max(p_c,p_o)$	t(23)	p
5	4.64	2.94	7.58	-2.586	.001	5.29	-0.568	.288
10	8.89	6.37	15.26	-4.965	.000	10.06	-0.089	.465
15	13.92	8.94	22.85	-6.130	.000	14.54	0.682	.251
20	17.74	11.24	28.98	-5.671	.000	18.25	2.220	.018
…								

Table 3. Test for violations of the race model inequality (RMI) for all (24) observers of Experiment 2. MI: multiple items, variable target location; SI: single item, variable location.
q: quantile of the RT distribution; p_c (p_o): probability of RTs to colour (orientation) targets faster than redundant target RT at the given quantile; p_c+p_o: sum of single target probabilities; $\max(p_c,p_o)$: largest single target probability.

Nevertheless, the lack of evidence for co-active processing, in particular in the MI condition, is at variance with several reports of parallel co-active processing of colour and orientation signals in search for singleton feature targets (Krummenacher et al., 2001, 2002; see also Zehetleitner et al., 2009, for a evidence of parallel co-active processing of orientation and luminance signals).
Leber and Egeth's (2006) finding that observers consistently used the (singleton or, respectively, feature search) strategy they had adopted in a first (training) phase of an experiment in the subsequent (test) phase, despite the fact that the carried-over strategy did not yield optimum performance, suggests that potential evidence of parallel co-active processing may have been obscured by strategy carry-over effects from the condition performed first to that performed second. In more detail, parallel co-active signal integration is not necessarily expected to occur if the decision on target presence requires (post-selective) access to feature representations (SI condition), rather than dimensionally integrated overall-saliency values (MI condition). On the assumption that the processing strategy

adopted in the single-item condition is maintained in the multiple-item condition, the lack of co-active processing in the MI condition might well be due to a carry-over effect displayed by observers who performed the MI condition after the SI condition.

While the MI condition can be performed perfectly in a (feature) processing mode necessary to solve the task in the SI condition, a carry-over effect in the opposite direction is unlikely, as responding does not logically require feature identity analysis in the MI condition, but does so in the SI condition (i.e., observers would have to change mode from the MI to the SI condition).

In order to address the possibility that carry-over of processing mode affected signal integration, violations of the RMI were tested for subsets of (each 12) observers who had started Experiment 2 with either the MI or the SI condition.

As can be seen from Table 4, the RMI was significantly violated at the 5%, 10% and 15% quantiles of the cumulative RT distributions in the MI condition provided that observers had not performed the SI condition beforehand. For all other observer groups and conditions, there was no evidence of RMI violations.

a) MI (N=12)

	Race inequality					Grice inequality		
q	p_c	p_o	p_c+p_o	t(11)	p	$\max(p_c,p_o)$	t	p
5	2.60	1.18	3.77	2.841	0.008	-	-	-
10	5.47	2.17	7.64	3.590	0.002	-	-	-
15	8.85	4.11	12.96	2.144	0.028	-	-	-
20	14.09	7.15	21.24	-1.191	0.129	-	-	-
…								

b) SI (N=12)

	Race inequality					Grice inequality		
q	p_c	p_o	p_c+p_o	t(11)	p	$\max(p_c,p_o)$	t(11)	p
5	3.49	2.23	5.72	-0.982	0.174	3.99	1.979	0.037
10	7.54	5.33	12.87	-4.697	0.007	8.49	1.986	0.036
15	12.61	8.05	20.66	-4.697	0.000	12.77	2.750	0.009
20	16.16	10.35	26.50	-4.235	0.001	16.48	3.751	0.002
…								

c) MI (N=12)

	Race inequality					Grice inequality		
q	p_c	p_o	p_c+p_o	t(11)	p	$\max(p_c,p_o)$	t(11)	p
5	5.58	1.98	7.55	-2.126	0.028	5.64	-0.761	0.231
10	10.46	4.31	14.77	-3.732	0.002	10.46	-0.506	0.311
15	14.05	6.60	20.65	-4.189	0.001	14.07	1.215	0.125
20	17.96	8.65	26.61	-3.572	0.002	17.96	2.037	0.033
…								

d) SI (N=12)

	Race inequality					Grice inequality		
q	p_c	p_o	p_c+p_o	t(11)	p	$\max(p_c,p_o)$	t(11)	p
5	5.80	3.66	9.45	-4.441	0.000	6.59	-2.218	0.024
10	10.24	7.42	17.65	-4.687	0.000	11.63	-1.960	0.038
15	15.22	9.83	25.05	-4.719	0.000	16.30	-1.528	0.077
20	19.32	12.14	31.46	-4.326	0.001	20.01	-0.010	0.496
…								

Table 4. Test for violations of the RMI for the subset of participants who started Experiment 2 with the multiple-items condition (a and b) and, respectively, with the single-item conditions (c and d). q: quantile of the RT distribution; p_c (p_o): probability of RTs to colour (orientation) targets faster than redundant target RT at the given quantile; p_c+p_o: sum of single target probabilities; $\max(p_c,p_o)$: largest single target probability.

RT distribution analysis – Grice inequality. Violations of the race model inequality revealed that in the MI condition of Experiment 2, redundant signals are integrated, in parallel, to co-activate the required detection responses. However, as such, the fact that no RMI were observed in the SI condition does not tell us whether responding is based on a parallel race of redundant-target signals or serial template matching. However, testing for violations of the Grice inequality, $\max\{P(RT < t \mid \mathrm{C}), P(RT < t \mid \mathrm{O})\} \leq P(RT < t \mid \mathrm{C\&O})$, permits this question to be decided (Grice et al., 1984; Townsend & Nozawa, 1995). The assumption of a parallel race underlying processing is violated if the largest probability of a response to a singly defined target having occurred at time *t* is significantly larger than the probability of a response to a redundant target having occurred at time *t*. Testing for violations of the Grice inequality was carried out only for the SI condition (as the RMI is violated in the MI condition, concurrent violations of the Grice inequality are logically impossible), for the entire sample of observers and separately for observers who completed the SI followed by the MI condition and vice versa. As can bee seen from Table 3 (right-hand panel), for the entire sample, although the largest single target probabilities [$\max\{P(RT < t \mid \mathrm{C}), P(RT < t \mid \mathrm{O})\}$] exceeds the redundant target probability

[$P(RT< t \mid C\&O)$], the Grice inequality was not significantly violated. Table 4 (right-hand panel) presents the results of the tests dependent on the condition observers completed first in Experiment 2. As expected, in the sample of observers who completed the SI condition first, the Grice inequality was violated significantly at the 5th, 10th and (marginally significantly) the 15th percentile. These violations show that, in the SI condition, redundant colour and orientation (feature) signals are checked serially. While there is statistically reliable evidence for this from observers who had not been exposed previously to the MI condition, those who had performed the latter condition first at least showed numerical violations of the Grice inequality (i.e., even for them, a parallel race of redundant target signals is unlikely).

Discussion

The fact that co-activation effects are demonstrable in the MI condition is consistent with Krummenacher et al. (2001, 2002; Zehetleitner et al., 2009), who provided evidence that these effects arise at a pre-selective stage, namely, the computation of cross-dimensional, overall-saliency signals. This is consistent with Töllner, Zehetleitner, Krummenacher, and Müller (2010), who recently showed an enhanced N2pc component for redundantly, relative to singly defined targets. As the N2pc is a marker of the event-related (difference) potential that is commonly assumed to reflect processes of attentional allocation (e.g., Eimer, 1996), the results of Töllner et al. provide electrophysiological support for an early, pre-selective effect of redundant-target coding. Furthermore, Krummenacher et al. (2001) showed that cross-dimensional signal integration in singleton detection tasks is modulated by inter-trial history: violations of the RMI were more marked if a redundantly defined target followed a redundantly defined target, rather than a singly defined target [7]. That is, if the integration stage is pre-selective, then the inter-trial effects in this type of task must logically also be operating at a pre-selective processing stage.

By contrast, the finding that there are no co-activation effects in the SI condition is consistent with the idea that the task demands in single-item conditions are entirely different (from those in multi-items conditions), involving post-selective feature checking. At least under the conditions of the present task, this appears to involve serial comparisons of the focally attended stimulus against the target memory templates, that is, it is not possible to make more than one such comparison at a time. Apart from the lack of RMI violations in the SI condition of Experiment 2, evidence for serial checking is provided by the violations of the Grice inequality, as well as the pattern of feature-specific, in addition to dimension-dependent, inter-trial effects in both Experiments 1 and 2.

[7] Due to insufficient numbers of trials, a similar analysis was not feasible for the MI data of Experiment 2.

Note that this is not to say that there are no conditions where a given stimulus can be compared in parallel to multiple target templates. For instance, Mordkoff und Yantis (1993) reported RMI violations in a task where observers were presented with one item only, a coloured letter; there were three possible shapes (e.g., X, O, H) and three colours (e.g., red, green, blue), with one particular shape and colour (e.g., X and red) being target-defining and the other two shape and colour alternatives being non-target features. Observers were instructed, in the example, to respond positively if the stimulus presented was an X (whatever its colour) or red (whatever its shape). That is, the stimulus had to be checked only against two target templates. Perhaps this can be done in a parallel-coactive fashion, given that the number of target alternatives to be kept in working memory is two. By contrast, parallel-coactive processing may no longer be possible when the number of possible alternatives is higher (four in the present experiments). This possibility requires further exploration. Whatever the answer, the number of possible alternatives had no effect in the MI condition (despite the fact that alternatives were exactly the same as in the SI condition), supporting the view that co-activation in this condition involves a different (namely: pre-selective) processing stage to the decision making stage in the SI condition.

Interestingly, observers who learnt to use a feature checking strategy to solve the first-performed, SI, task showed no co-activation effects when they were later presented with the MI task. While this is consistent with the idea that the multi-item task can be performed using a (feature analysis) processing mode adopted to solve the single-item task (but not vice versa), one might ask why there were no co-activation effects for this observer group at all – assuming that there is signal integration at the first, pre-selective stage of processing. Restated, post-selective feature checking effects should be additive with pre-selective co-activation effects. However, variance created at the post-selective stage may have swamped effects at the pre-selective stage. Alternatively, or additionally, serial checking of features at the secondary stage could have impacted, in top-down manner, on the way pre-selective signals are integrated (see also Müller, Krummenacher & Heller, 2004, and Pan, Xu & Soto, 2009, who showed an influence of post-selective working memory demands on pop-out target detection).

General Discussion of Experiments 1 and 2

In summary, the present experiments revealed that the pattern of inter-trial effects (indicative of the memory-based mechanisms of task performance) differs between multiple-items (search) tasks, in which responding can be based on simple target detection, and single-item (non-search) tasks, in which responding requires stimulus analysis beyond detection. The fact that there was no feature-specific inter-trial effect in the standard pop-out search tasks (with multiple items and variable target location) is consistent with saliency-based processing accounts (e.g., Itti & Koch, 2000, 2001; Müller et al., 1995; Wolfe, 1994). According to these visual selection and response decisions are based (more or less directly) on supra-dimensional saliency signals that do not (or no longer) carry information about the specific features that give rise to them (see Müller & Krummenacher, 2006). By contrast, the

fact that there are feature-specific effects in the single-item, non-search task is consistent with the idea that this task requires post-selective (focal-attentional) feature analysis. The present data suggest that the latter process involves a serial component, of comparing the stimulus against a set of target templates held in working memory. Consistent with this, there was no evidence of co-active processing of dimensionally redundant target features in the single-item task; also, a parallel race of such features could be ruled out by the violations of the Grice inequality in Experiment 2, which leaves only the alternative of serial processing.

Although the pattern of inter-trial RT effects is consistent with serial checking, one might argue that the rate of checking – some 10–20 ms per feature – is too fast to be consistent with a genuinely serial process. But it may be that multiple feature alternatives are processed simultaneously at the focal-attention stage, while however there is a serial order in which they enter this stage (along the lines of the 'car wash' analogy suggested by Wolfe, 2003).

Note that this is the very pattern that would also be expected on the Boolean Map Theory recently proposed by Huang and Pashler (2007). Conversely, in the multi-item task, redundant target (i.e., feature contrast) signals are integrated across dimensions, giving rise to violations of the race model inequality.

This pattern of effects argues that there are two relatively independent sources of inter-trial effects in the two tasks: one located on a pre-selective processing stage, where signals are coded in a feature-unspecific, but (across dimensions) parallel co-active processing architecture; and the other on a post-selective stage, where signals are processed in terms of precise feature information, in a serial fashion (with intra-dimensional feature switches given priority over cross-dimensional switches).

Accordingly, with regard to the question posed at the beginning, the assumption that there is only one weighting system involved in the two types of task (as proposed by Mortier et al., 2005) is not tenable. Rather, there are multiple weighting systems operating at different levels. This is consistent with the Dimension Weighting account developed by Müller and his colleagues (e.g., Müller et al., 1995, 2003; Found & Müller, 1996). While this account, thus far, has only focused on the pre-selective weighting mechanism, it admits the possibility of other short-term memory mechanisms operating at later stages in the processing hierarchy. In contrast, the single-mechanism account of Mortier et al. (2005) admits only the possibility of post-selective memory buffering, and would thus be unable to explain the existence of any inter-trial effects arising from earlier processing stages.

Apart from the results revealed by the present experiments, there are a number of behavioural and brain-imaging studies that support the notion of pre-selective weighting. In particular, Zehetleitner, Krummenacher, Geyer, and Müller (2010) have recently shown cross-dimensional inter-trial transition to affect perceptual sensitivity in a pop-out localization task, indicative of an effect originating at an early level of (saliency) coding: sensitivity was reduced for a target defined in a changed dimension, as compared to a repeated dimension (see also Müller & O'Grady, 2000, who found costs in terms of

sensitivity when observers had to judge dual object attributes in different dimensions, rather than in the same dimension).
Furthermore, neuro-imaging investigations of dimension-based inter-trial effects in pop-out search tasks (Pollmann et al., 2000, 2006a) have revealed significant BOLD signal increases in visual sensory areas (V4 and hMT+) contingent on the repetition versus change of the target-defining dimension (colour and motion, respectively) across consecutive trials. Sensitivity of sensory visual areas to repetitions of the relevant dimensions argues in favour of an early, perceptual locus of dimensional weighting. That this (perceptual) locus is indeed pre-selective is supported by a study of Töllner et al. (2008), who investigated ERP correlates of dimension-based inter-trial effects using a compound-search task (Bravo & Nakayama, 1992; Duncan, 1985), where the target- and the response-defining features were dissociated: participants had to respond to the orientation of a grating within a form or a colour target. Analysis of the N2pc component revealed significant dimensional inter-trial effects in N2pc peak latencies (as well as amplitudes): the N2pc peaked earlier (and its amplitude was larger) with dimension repetitions rather than changes. This adds support to the notion that dimensional weighting modulates (pre-selective) signal coding processes that form the basis for the allocation of focal attention.

In summary, it is contended that the inter-trial effects in pop-out search (multi-items) and non-search (single-item) tasks are dissociable, reflecting different underlying memory mechanisms. Although dissociable, there may also be possible interactions between the two mechanisms, as evidenced, for instance, by the lack of co-active processing in a MI task following performance of an SI task. The present results suggest that, when the system is set for feature analysis, this impacts (perhaps in a top-down manner) on the weight distribution at the pre-selective level, which in turn determines the ability of multi-dimensional target signals to co-activate the required (detection) response. Further work is necessary to characterize these interactions in detail.

Electro-physiological evidence

Further evidence for a perceptual basis of redundancy gains comes from Töllner, Zehetleitner, Krummenacher and Müller (2010), who investigated event-related potentials to redundantly (colour and orientation) relative to singly (colour or orientation) defined singleton targets in a feature search task. Töllner et al. (2010) aimed to differentiate between the two alternative hypotheses about the stage of dimensional co-activation integration discussed above focusing on two components of the EEG signal; the N2pc and the LRP. They reasoned that if co-activation was to occur (or at least to co-occur) at a pre-attentive processing stage (Krummenacher et al., 2001, 2002) there should be a modulation of the ERP component reflecting allocation of focal attention to redundant versus single targets, the N2pc component (Eimer, 1996; Luck & Hillyard, 1994). If, however, co-activation occurs only at a post-selective stage, after focal attention has been allocated to the target (Cohen & Feintuch, 2002; see also Miller, 2007), electrophysiological correlates of the redundant signals effects were expected to be found in components related to response-selection or -execution, the (stimulus- or response-locked) LRP component. More importantly, in the case of LRP modulations, no modulation of the N2pc to redundant relative to single targets must be observed; the N2pc would not be expected to show a redundancy gain in latencies or amplitudes. Töllner et al. (2010) presented observers with homogeneous stimulus arrays containing yellow horizontal bars among which a colour (red horizontal), orientation (yellow vertical) or redundant (red vertical) singleton was to be detected. On the level of the behavioural analysis, they observed redundancy gains (faster RTs to redundant compared to single targets), further, the RMI was significantly violated providing evidence in favour of a co-active activation model (Krummenacher et al., 2001, 2002; Miller, 1982). ERP-wise modulations of the N2pc were found to reflect the behavioural RT pattern; N2pc latencies to redundant targets were shorter compared to N2pc latencies to colour or orientation singletons. N2pc amplitudes were more pronounced for redundant and orientation compared to colour targets. Töllner et al. (2010) concluded that according to these results there must have been differential processing rates within pre-attentive processing stages according to the target identity (N2pc latencies modulations). The N2pc as a marker of the transition from pre-attentive to focal-attentional processing reflects the pre-attentive stimulus encoding rate (Töllner et al., 2008) which was faster for redundant relative to single colour and orientation targets. The redundant signals effect seems therefore to be generated (at least in part) at pre-attentive perceptual processing stages providing the basis for faster focal-attentional target selection. The enhanced N2pc amplitudes for redundant and orientation relative to colour targets were interpreted as indexing a higher amount of attentional-resource allocation to these targets.

However, the LRP analyses revealed substantially a faster onset of the stimulus-locked LRP to redundant relative to single targets and a significantly faster onset of the colour compared to the orientation stimulus-locked LRP. The stimulus-locked LRP amplitudes were not modulated. Under the assumption that the stimulus-locked LRP latencies inherently include any pre-selective processing differences between the conditions (additive process components), Töllner et al. (2010) subtracted the

N2pc latencies from the stimulus-locked LRP latencies in order to examine redundancy-caused latency gains at stages post selection but prior to response generation. The difference between N2pc (-23.5 ms) and stimulus-locked LRP (-23.5 ms) mean redundancy gains (redundant latencies minus averaged colour and orientation latencies) revealed a value of exactly zero.
The response-locked LRPs (latencies and amplitudes) were independent of the target identity; redundancy gains were not reflected in the response activation and execution stages.
Based on their findings of N2pc and stimulus- and response-locked LRP modulations, Töllner et al. (2010) proposed a pre-attentive perceptual basis of the redundant signals effect in feature singleton search tasks in which the redundant signal stem from identical locations.

Experiment 3: N2pc modulations by context-based redundancy gains

Purpose of the present study

According to Krummenacher et al. (2001, 2002) the redundant signals effect is assumed to arise at a pre-selective processing stage that follows dimension-based saliency representations. The first assumption, i.e. the pre-attentive generation of the effect was recently verified in an EEG study by Töllner et al. (2010) who found RT redundancy gains to be reflected in a substantial latency shift of the N2pc in redundant relative to non-redundant displays. The onset of the N2pc was earlier in redundant signal compared to single signal trials. No modulation of the response-related LRP components was observed.
The assumption that responses are based on an integrated saliency signal, that is, that dimensional signals are integrated at a level subsequent to dimensional saliency representations, has recently been challenged by Li (2002; Koene & Zhaoping, 2007) who argue that redundancy gains arise at an even earlier level than suggested by Krummenacher and colleagues, namely the neural representation of visual information in primary visual cortex (V1). In order to address the challenge posed by the V1-hypothesis, Krummenacher and Müller (unpublished manuscript) adapted the redundant singleton search paradigm by presenting, in target-present trials, always the same target (a green vertical bar) but making the target differ from distractors on either a single dimension or on dual dimensions by changing the features of the distractors. Distractors were either red and vertical, green and tilted (single-dimension difference), or red and tilted (dual-dimension difference) bars. In the adopted redundant signals paradigm, participants could be expected to adopt a so-called ‘feature search mode’ (Bacon & Egeth, 1994; see also section 5 of the present thesis). Since observers always search for the same (green vertical) target, only the feature detectors signalling the presence of the relevant feature(s) would be activated in feature search mode (s.a., Treisman & Gelade, 1980; Treisman & Sato, 1990) and no modulation of search RTs (or ERPs) should be observed (processing can be assumed to take place in the area V1; Li, 2002; Koene & Zhaoping, 2007). In a search condition with a target

constantly defined by the same feature, adopting a strategy of detecting the presence of a green vertical item should abolish any redundancy gains. According to Krummenacher et al.'s saliency hypothesis, however, redundancy gains would be observed also in the constant-target condition. Results (Krummenacher et al., unpublished manuscript) showed that, compared to the standard search condition in which the dimension-based target definition changes randomly across trials, redundancy gains of a similar magnitude are observed in the constant-target condition. Further, Miller's (1982) race model inequality is violated indicating that signal integration is co-active in nature.

Overview of Experiment 3

The present Experiment 3 was conducted in order to replicate the findings of Krummenacher and Müller (unpublished manuscript) and to investigate the similarity of the EEG effects observed in the constant target conditions (Töllner et al. 2010). In Experiment 3, event-related potentials in the constant target condition were analysed and compared with the event-related potentials of Töller et al.'s (2010) variable-target condition. Therefore, the stimulus-material used by Töllner et al. (2010) was adapted for Experiment 3; target identity was held constant and distractors changed randomly across trials as Krummenacher et al.

Method

Participants. Twelve observers took part in the EEG experiment, with age ranging from 20 to 28 years (median age 23.8 years); ten observers were female. All participants had normal or corrected-to-normal vision, including colour vision and only one of them was left-handed. Participants were paid (CHF 20 per hour) or received course credits. All observers were naïve as to the purpose of the experiment and most of them had taken part in visual search studies before.

Stimuli, procedure, and apparatus. Observers were presented with search displays consisting of 34 items; 6, 12 and 16 items, respectively, were evenly distributed on three imaginary circles with radii of 4.5°, 8.5° and 12.5° of visual angle, respectively. A white fixation cross (+) was presented at the centre of the screen during the whole experiment. Stimuli were bars subtending 0.6° x 2.7° of visual angle in width and height, item orientations were uniformly jittered within a range of ± 8° of visual angle. A target item was presented at one randomly selected location of the six lateral positions of the middle circle. In half of the trials, the target appeared on the left side of the fixation cross, in the other half it was presented on the right side.

The identity of the singleton target was counterbalanced across participants, but within one (group of) observer(s) the singleton target was always defined by the same feature(s). Colour-defined features were orange (CIE .544, .393; 3 cd/m²) and yellow (CIE .456, .469; 3 cd/m²); orientation-defined features were horizontal and vertical. The distractor types changed randomly from trial to trial. The distractors defined each search trial in either a single dimensional difference (context) with the target differing from distractors in a unique dimension (colour or orientation) or a dual redundant dimension

difference (context) with the target differing from distractors on both (colour and orientation). As an example, the target was always coloured orange and vertically orientated, whereas distracters were randomly either coloured orange and horizontally orientated (orientation display), or coloured yellow and orientated vertical (colour display), or coloured yellow and horizontally orientated (redundant display).

Participants were instructed to maintain fixation during the whole trial. Responses were given by pressing one of two pre-defined keys for target present and absent trials, respectively. Participants were instructed to respond as quickly and accurately as possible. Half of the observers started by depressing the right key with the right index finger in target present trials and the left key with the left index finger in target absent trials. For the other half of the observers it was the other way round. The response key mapping was changed in the middle of the experiment for all participants.

The whole experiment consisted of 1296 trials, divided in 18 blocks of 72 trials; half of the trials were target present trials and the three experimental conditions (colour, orientation, colour and orientation) were presented randomly, but appeared equally often within each block. Each trial started with the presentation of a white fixation cross for 500 ms, followed by the search array which was presented for 200 ms. The trial was terminated by the observer's response after which the next trial began with a variable inter-trial interval of 1950 to 2050 ms. In the case of an erroneous response a one-second feedback display showing the word 'error' was shown before the start of the next trial. Accuracy and RTs were fed back at the end of each block. Before the experiment and before the change of the response keys, observers completed a short block of 34 trials to (re-) familiarize them with the task. Participants were seated in a dimly illuminated cubicle. Stimulus presentation, timing, and response recording were controlled by a Pentium PC running under the Windows XP operating system and using "PsychToolbox" software for MATLAB (Mathworks, Inc.). Stimuli were presented at 100 Hz on a 19" CRT monitor (Philips Brilliance P202), at a screen resolution of 1280 × 1024 pixels. Observes viewed the display from a distance of approximately 75 cm.

RT data analysis. The RT data to the four possible target identities were pooled. The analysis of the RT data is divided in two sections, the first of which reports mean RT redundancy gains, and the second examines the entire RT distributions. In the first analysis, mean RTs to the two singly defined (colour or orientation) and to the redundantly (colour and orientation) defined search displays were subjected to a one-way repeated-measures ANOVA with the single factor Context Condition (colour, orientation, redundant). In the second analysis, the single and redundant target cumulative RT distributions were tested for violations of Miller's (1982) race model inequality (RMI) in order to examine whether the redundant colour and orientation condition was processed in a parallel-coactive fashion. In detail, it was tested whether the fast part of the RT distribution of redundantly defined search displays was significantly faster than the RTs in the fastest singly defined (colour, orientation) displays. Formally, the RMI states that $P(RT < t \mid \mathrm{CO}) \leq P(RT < t \mid \mathrm{C}) + P(RT < t \mid \mathrm{O})$. The summed probability ($P(RT < t \mid \mathrm{C}) + P(RT < t \mid \mathrm{O})$ that a response at a given point in time t is given in displays

defined by colour (C) or orientation (O) must not be smaller than the probability ($P(RT<t) \mid CO$) of a response to a redundant (CO) target at time *t* for the assumption of a parallel race to be satisfied. Violations of the RMI indicate that both colour and orientation signals contribute to the co-activation of a subsequent common module.

EEG recording and data analysis. The continuous electroencephalogram (EEG) was DC-recorded at a digitization rate of 1000 Hz, using 64 active electrodes embedded in elastic caps (actiCAP, BrainProducts, Munich) and placed according to the international 10-10 System (American Electroencephalographic Society, 1994). Horizontal (HEOG) and vertical (VEOG) eye activity was monitored and recorded at electrode positions F9/10 and Fp1/inferior orbit of the eye, respectively. Electrophysiological signals were amplified with a 0.1- to 250-Hz band-pass filter using BrainAmp amplifiers (BrainProducts, Munich) and were filtered offline with a 1- to 40-Hz band-pass (Butterworth zero phase, 24 dB/oct). All electrodes were referenced to FCz and offline re-referenced to linked mastoids (corresponding to electrode sites TP9/TP10). Impedances were kept below 5 kΩ. The EEG was epoched into 800 ms segments from 200 ms prior (used for baseline correction) to 600 ms post display onset events. A 200 ms pre-stimulus baseline correction was applied. Trials with saccades (voltage exceeding ± 30 µV in the HEOG channels) or eye blinks (voltage exceeding ± 60 µV in the VEOG channels) were excluded from analysis. Muscular artefacts (voltage exceeding ± 80 µV with permitted maximal voltage steps/sampling point of 50 µV in all channels) and dead channels with activity lower than 0.5 µV were removed from analysis on an individual channel basis. Event-related potentials (ERPs) were averaged relative to the 200 ms pre-stimulus baseline separately for each experimental condition (colour, orientation, and redundant context displays), but pooled for the four possible target identities.

The N2pc (posterior contralateral activity after the N2 component) reflecting focused attention (Eimer, 1996; Luck & Hillyard, 1994; Woodman & Luck, 1999) onto a potential target item was quantified by subtracting ipsilateral from contralateral ERPs relative to the display side of the singleton obtained at lateral posterior electrode sites PO7/PO8 ERPs. The stimulus-locked LRP (lateralised readiness potential) waveforms reflecting target identity processing and response selection were calculated by subtracting ipsilateral ERPs at electrodes C3/C4 from contralateral ERPs at these electrode sites with respect to the uni-manual hand responses. N2pc and stimulus-locked LRP latencies were determined individually as the maximum negative deflection within the time window of 150 to 350 ms post-stimulus or, respectively, 200 pre- to 600 ms post-stimulus. For the computation of response-locked LRP waveforms reflecting the motor execution stage, the whole EEG was re-epoched in 4000 ms (2000 ms before and after stimulus onset) segments in order to get rid of stimulus-locked LRP waveforms. The baseline was corrected on the basis of a 200 ms pre-stimulus interval and the EEG was divided in 800 ms segments ranging from 600 ms before to 200 ms after response. Again, with respect to the uni-manual hand responses ipsilateral ERPs at electrodes C3/C4 were subtracted from contralateral ERPs. N2pc and LRP amplitudes were calculated by averaging five sample points before

and after the corresponding maximum deflection. N2pc latency analyses were based on peak latencies. For the LRP latency analyses, onset latencies were used, which were determined according to Ulrich and Miller's (2001; Miller, Patterson & Ulrich, 1998) jackknife-based scoring method. For the stimulus-locked LRPs, the time at which 50% of the maximum LRP amplitude was reached was taken as onset latency, for the response-locked LRP the 90% criterion was applied. Latencies and amplitudes of all components were analyzed in one-way repeated-measures ANOVAs with the factor context condition (colour, orientation, redundant), and, for LRP onset latencies, F-values were corrected according to Ulrich and Miller (2001).

Result - Behavioural data

RTs faster than 200 ms or slower than 1000 ms were excluded from analysis as anticipatory or exceedingly slow reactions (0.4% of all trials). Additionally, RTs exceeding mean RTs by more than ± three standard deviations of the mean were excluded from analysis (1.4% of all trials).

Errors. Errors in target absent (false alarms) as well as in target present (misses) trials were analysed by means of an one-way repeated measures ANOVA with the factors error (false alarms, misses) and context condition (colour, orientation, redundant). The main effect of error [$F(1,11) = 14.151$, $p = .003$] a well as the main effect of condition [$F(2,22) = 10.665$, $p = .001$], but not the interaction [$F(2,22) = 2.086$, *n.s.*] were statistically significant. In redundant trials(2.7 %) markedly fewer errors were made relative to single colour (5.0%) and orientation (5.3%) trials, ruling out a speed-accuracy trade-off underlying the speeded RTs to redundant trials (see below, Mean RT redundancy gains). In general, more misses than false alarms were made in single colour (6.0% vs. 4.0%) and orientation (5.8% vs. 4.9%) trials as well as in redundant (2.9% vs. 2.4%) trials.

Mean absent and present RTs. Mean target absent and present RTs were analysed in three independent one-way repeated measures ANOVAs with the factor target (absent, present). Only the ANOVA for redundant trials revealed the main effect to be statistically substantial [$F(1,11) = 8.501$, $p = .014$]. Redundant target present trials (426.3) were responded to faster relative to redundant target absent trials (443.6 ms). However, RTs to colour (454.9 ms) and orientation (455.4 ms) target present trials were statistically equally fast to RTs to the according colour (453.5 ms) and orientation (457.9) target absent trials.

Mean RT redundancy gains. Mean correct-response RTs of the three types of target present trials were subjected to a one-way ANOVA with the factor context condition (colour, orientation, redundant). The effect of condition was highly significant [$F(2,22) = 22.903$, $p < .001$]. The differences in RTs between each of the two single signal conditions colour (454.9 ms) and orientation (455.4 ms) compared to the redundant signal (426.3 ms) was statistically substantial (pair-wise comparisons: orientation vs. redundant ± 29.1 ms; colour vs. redundant ± 28.6 ms, both *p*s < .001), whereas there

was no significant difference between the two single signals (pair-wise comparisons: colour vs. orientation difference: 0.5 ms, $p = .935$).

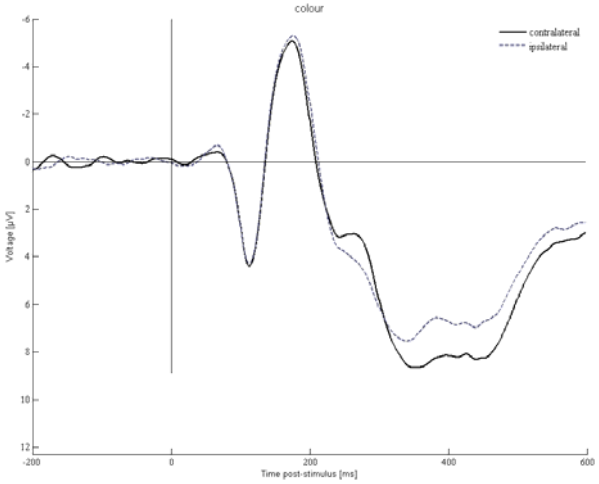
RT distribution analysis. In order to examine whether the observed RT redundancy gains were the result of parallel co-active processing or a parallel-race between single signals, Miller's (1982) RMI [$P(RT < t \mid CO) \leq P(RT < t \mid C) + P(RT < t \mid O)$] was applied to test the RT distributions for violations. The RMI analyses show that the summed probabilities for C and O trials were below the criterion (C&O) value. As can be seen from Table 5, the RMI was significantly violated at the 5% and 10% quantiles of the cumulative RT distributions. The finding of RMI violations rules out a parallel race model underlying processing.

			Race inequality		
q	p_c	p_o	p_c+p_o	t(11)	p
5	1.3	2.3	3.6	2.568	.013
10	3.4	4.8	8.1	1.998	.036
15	6.3	7.4	13.7	0.807	.218
20	9.7	11.0	20.7	-0.350	.366
…					

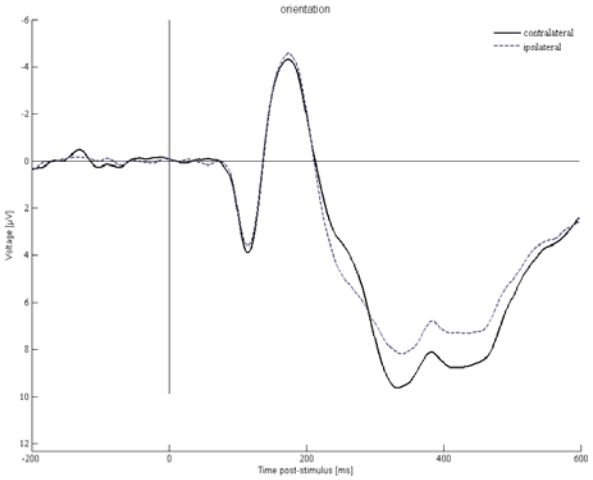
Table 5. Test for violations of the race model inequality (RMI) for all (12) observers of Experiment 3. q: quantile of the RT distribution; p_c (p_o): probability of RTs to colour (orientation) signals; p_c+p_o: sum of single signal probabilities.

Results - EEG data

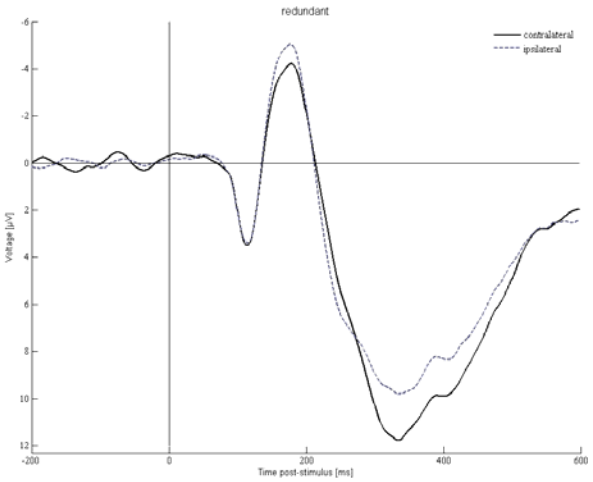
Figure 11 presents the N2pcs components obtained at PO7/PO8 contralateral and ipsilateral to the side of the singleton target, separately for the conditions colour, orientation and redundant displays (a-c) and the difference between waveforms (ipsilateral activity subtracted from contralateral activity) for each of the three experimental conditions (d). A solid N2pc was elicited in all three conditions. N2pc latencies and amplitudes were subjected to separate one-way ANOVAs each with the factor context condition (colour, orientation, redundant). For N2pc latencies, the effect of condition was statistically substantial [$F(2,22) = 16.264$, $p < .001$]. The fastest latencies were obtained for redundant signals (235.9 ms), followed by the single signal orientation (261.8 ms) and colour (279.4 ms) latencies. Pair-wise comparisons revealed the latency differences between all conditions to be significant: colour signals were slower than orientation signals (± 17.6 ms, p = .047) and colour (± 43.5 ms, $p = .003$) as well as orientation (± 25.9 ms, $p = .005$) signal latencies were slower than redundant signals latencies. For N2pc amplitudes, there was no substantial effect of condition [$F(2,22) < 1$]. None of the amplitudes for colour (-1.7 µV), orientation (-2.0 µV) and redundant (-2.0 µV) signals was markedly more pronounced compared to other amplitudes.


colour
contralateral
ipsilateral
Voltage [µV]
Time post-stimulus [ms]

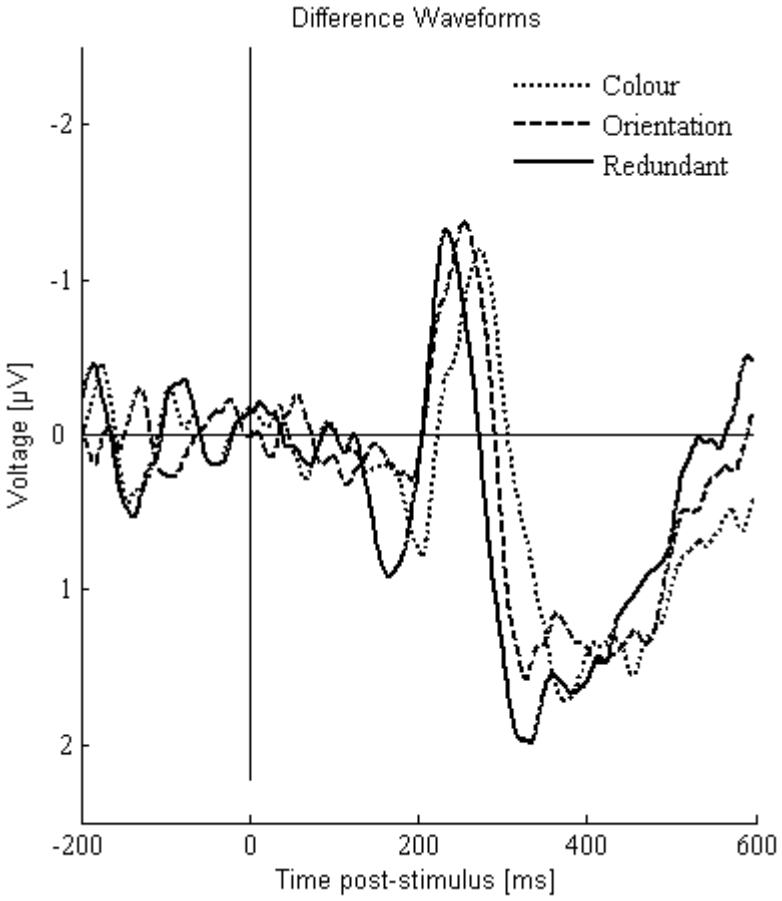
a)


orientation
contralateral
ipsilateral
Voltage [µV]
Time post-stimulus [ms]

b)


redundant
contralateral
ipsilateral
Voltage [µV]
Time post-stimulus [ms]

c)



d)

Figure 11. Grand-average N2pc components elicited in the 600 ms interval after stimulus onset at electrode positions PO7/PO8 contralateral and ipsilateral to the side of the singleton target, separately for colour (a), orientation (b) and redundant (c) displays. N2pc difference waveforms (d) obtained by subtracting ipsilateral from contralateral activity for each of the three experimental conditions.

Figure 12 shows the stimulus-locked LRP difference waveforms (contralateral activity minus ipsilateral activity) obtained at C3/C4 electrode sites for the three experimental conditions (colour, orientation, redundant signals). In analogy to the N2pc, stimulus-locked LRP amplitudes were analyzed in a one-way ANOVA. The ANOVA revealed a significant main effect [$F(2,22) = 6.130$, $p = .008$], and pair-wise comparisons showed the amplitudes to colour (-1.8 µV) and redundant (-2.4 µV) signals to differ substantially ($p = .012$). Between orientation (-2.2 µV) and redundant and between colour and orientation amplitudes no marked difference was observed. Stimulus-locked LRP onset latencies (determined by the jackknife-based scoring method with a 50% maximal amplitude criterion; Miller et al., 1998; Ulrich & Miller, 2001) were subjected to a repeated measures ANOVA. The effect of context condition was significant [$F_c(2,22) = 332.140$, $p < .001$]; latencies to redundant signals (278.5 ms) were fastest, followed by latencies to orientation (293.2 ms) and colour (299.8 ms) signals. However, additional t-tests unveiled none of the differences to be significant ($t_c(11) = -2.330$, *n.s.*). F- and t-values were corrected according to the procedure proposed by Ulrich and Miller (2001).

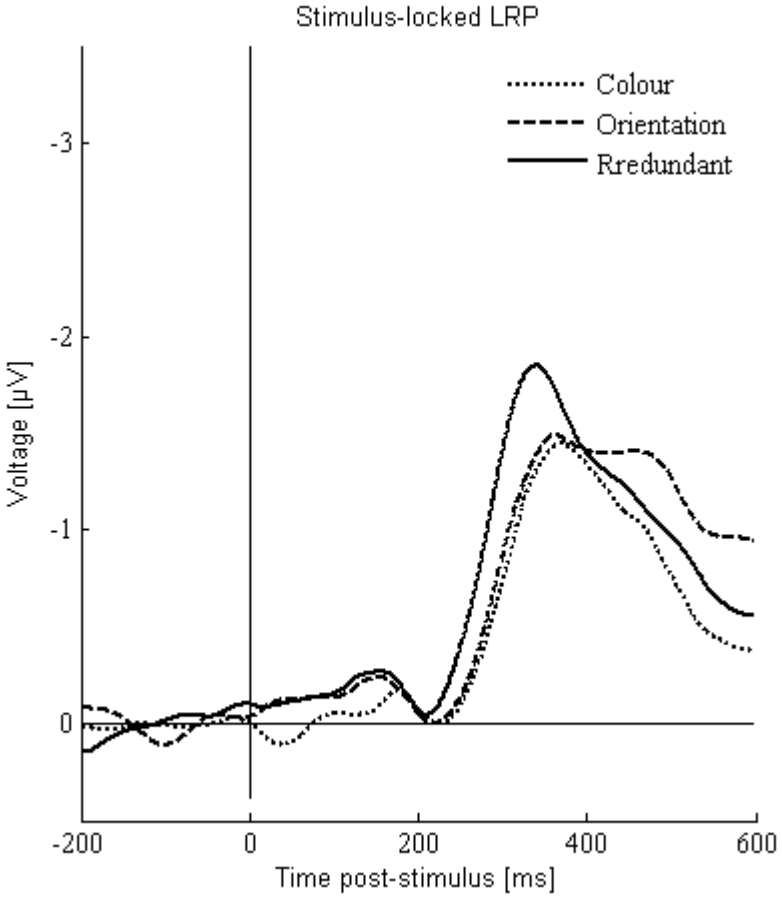


Figure 12. Stimulus-locked Lateralised Readiness Potential (LRP) elicited in the 600 ms interval after stimulus onset at electrode positions C3/C4 for each experimental condition.

Figure 13 shows the response-locked LRP differences (contralateral activity minus ipsilateral activity) obtained at C3/C4 electrode sites for the three context conditions (colour, orientation, redundant difference signals). The ANOVA of the amplitude yielded a significant main effect of context condition [$F(2,22) = 3.781$, $p = .039$] and pair-wise comparisons showed that the amplitude to colour (-2.5 µV) compared to redundant (-2.8 µV) signals was significantly less pronounced ($p = .044$). The amplitudes to orientation (-2.9 µV) and redundant (-2.8 µV) and to colour (-2.5 µV) and orientation signals were not statistically significantly different. The one-way ANOVA of response-locked LRP latencies (determined by the jackknife-based scoring method with a 90% maximum amplitude criterion; Miller et al., 1998; Ulrich & Miller, 2001) revealed a significant main effect [$F_c(2,22) = 230.883$, $p < .001$], but, similar to stimulus-locked LRP latencies, further t-tests investigating latency differences between the three context conditions colour (518.5 ms), orientation (521.1 ms) and redundant (515.5 ms) were not statistically significant ($t_c(11) = -1.513$, *n.s.*). F- and t-values were corrected according to the procedure proposed by Ulrich and Miller (2001).

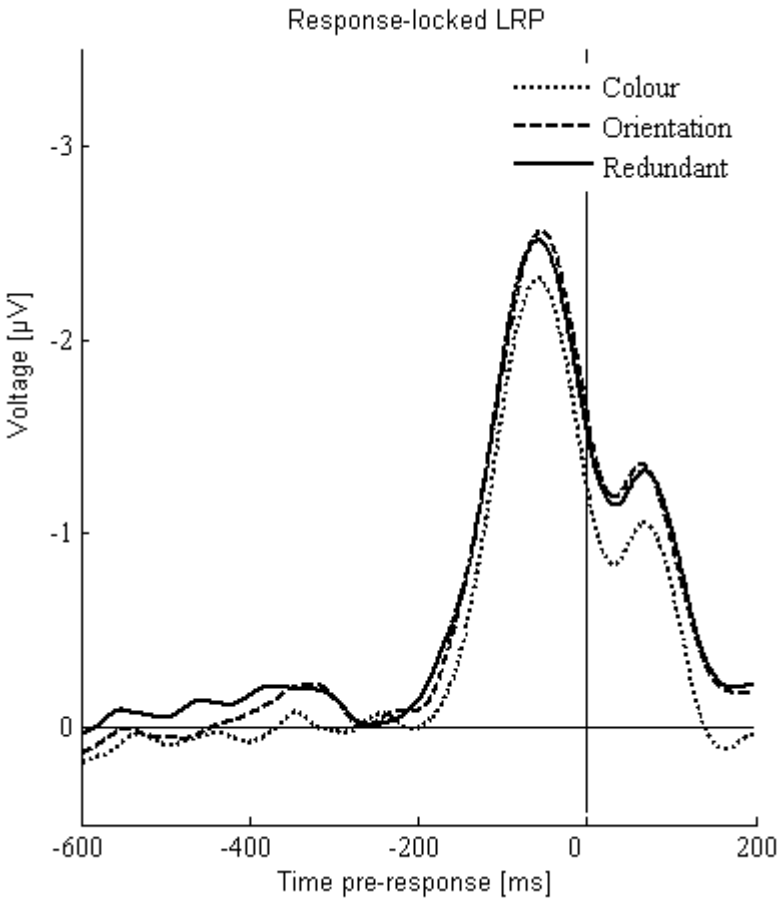


Figure 13. Response-locked Lateralised Readiness Potential (LRP) elicited in the 600 ms interval prior to response at electrode positions C3/C4 for each experimental condition.

Discussion

The present experiment was conducted in order to replicate the findings of Krummenacher and Müller (unpublished manuscript), who found RT redundancy gains and violations of the RMI (constituting evidence for pre-selective co-active processing of dimensional signals) in search for singleton feature targets constantly defined by the same two features (green, vertical) amongst homogeneous distractors differing from target on a single dimension (colour or orientation) or a redundant dimension (colour and orientation) context. The behavioural data of the present Experiment 3 revealed exactly the same results as in Krummenacher et al.'s study. RTs to redundant signals were markedly expedited compared to single signals, although the target remained constant and only the context signal(s) changed randomly across experimental trials. Additionally, substantial violations of the RMI (Miller, 1982) were obtained, confirming co-activation of dimension-specific signals prior to focal attentional target selection. These findings alone rule out the V1 hypothesis formulated by Li (2002; Koene & Zhaoping, 2007). If redundancy gains would arise at an earlier level than the dimension-based saliency representations, any redundancy gains should have been abolished with the present task, since across trials, always the same features (green, vertical) had to be detected. The data suggests that participants

did not adopt a feature search mode (Bacon & Egeth, 1994). Rather, they preferred detecting the target on the basis of dimension-specific saliency activations; that is, using a 'singleton search mode' (Bacon & Egeth, 1994).

A finding of the present experiment that seems to be in line with Bacon and Egeth's (1994) feature search mode, but in contrast to the Töllner et al. (2010) study, is the equality of the N2pc amplitudes. However, this result was expected. In the study by Töllner et al., the target-defining properties were varied rather than the context properties as in the present Experiment 3. In other words, in Töllner et al.'s experiment, the target was either defined by colour or orientation or by both colour and orientation and the distracters always remained the same whereas in the present study the target remained constant and the distractors changed. With the present paradigm, the target was indirectly defined by colour or orientation or both by modulation of the context of the stimulus display. Thus, taking the N2pc amplitude as index of the amount of attentional resource allocation, in the present study, the N2pc amplitudes between the experimental conditions did not differ significantly because, in the end, they were all answers to (for example) an orange vertical signal. Clearly, in order to provide evidence for a feature search mode and a purposeful search for known features one would also expect to find the N2pc latencies unaffected by context conditions. But in line with Töllner et al. (2010) the behavioural RT redundancy gains were reflected in the latencies of the N2pc component; N2pc latencies to redundant signals were markedly shorter compared to N2pc latencies to single signals of both the colour and orientation dimensions. The N2pc is understood to reflect the allocation of focal attention based on perceptual stimulus attributes (Eimer, 1996; Luck & Hillyard, 1994; Woodman & Luck, 1999) and can be interpreted as the end mark of pre-attentive sensory encoding. The N2pc latency therefore indexes the pre-attentive processing speed which was significantly enhanced in the present Experiment 3 for redundant relative to single dimensional difference signals. Consequently, the pattern of N2pc amplitude and latency modulations in the present study can be interpreted as a reflection of resource allocation (Krummenacher et al., 2001, 2002) rather than feature processing (Bacon & Egeth, 2994; Koene & Zhaoping, 2007; Li, 2002).

Supporting Töllner et al. (2010) the speeded N2pc amplitude-latencies to redundant signals can be interpreted as further evidence for an involvement of pre-attentive perceptual processes in the generation of the redundant signals effect. The mean (manual) RT gain for redundant signals (± 28.9 ms / ± 28.6 ms relative to single colour, ± 29.1 ms relative to single orientation) is of a magnitude comparable to the mean N2pc latency gain for redundant signals (± 34.7 ms / ± 43.5 ms relative to single colour, ± 25.9 ms relative to single orientation). This pattern can be taken to suggest that the redundant signals effect was exclusively generated on a pre-attentive perceptual processing stage, constituting the basis for an efficient target selection mechanism. As response-locked LRP latencies

were not at all modulated by context condition an involvement of the response-execution stage in the generation of the redundant signals effect can be ruled out.
However, although the latency differences of the stimulus-locked LRP did not reach statistical significance, there seems to be a tendency for faster processing of redundant signals relative to single signals. According to the logic of additive factors (Donders, 1868, 1969), this finding is not surprising. Both components, the N2pc as well as the stimulus-locked LRP are, as already suggested by the names, locked to the onset of the stimulus. Therefore the chronometry of the stimulus-locked LRP cannot be independent of possible latency shifts of preceding components as the N2pc, or more general, response-selective processing stages cannot be independent of preceding perceptual processing stages (Müller & Krummenacher, 2006). Therefore, the pattern of latency variations caused in early processing stages is expected to be consistently found again in later processing stages (as long as the reference event is not changed). This was revealed in the present data. Redundant signals were processed fastest at the level of the N2pc as well as at the level of the stimulus-locked LRP, followed by colour signals and orientation signals as the slowest, at both stages, the N2pc and the stimulus-locked LRP.

It should be noted that the mean latency redundancy gain at the stage of the N2pc (of ± 34.7 ms as compared to ± 43.5 ms relative to single colour, ± 25.9 ms relative to single orientation) was larger compared to the mean latency redundancy gains at the stage of the stimulus-locked LRP (± 18.0 ms as compared to ± 21.3 ms relative to single colour, ± 14.7 ms relative to single orientation). It seems that after focal attention allocation at the stage of target identity processing and response-selection some advantage (of ± 16.7 ms) for redundant signals was lost again. The mean latency redundancy gain of both components, the N2pc and the stimulus-locked LRP (± 26.4 ms) indeed is very close to the RT redundancy gain (± 28.9 ms) as measured behaviourally. This might be seen as further evidence that post-selective response selection processes are not completely independent of pre-selective target selection processes (Müller & Krummenacher, 2006) and that both processing stages contribute to the behaviourally measurable RT redundancy gain. This was also seen in the compound search experiment of Töllner et al. (2008). Behaviourally, they observed RTs-benefits for target dimension repetition trials (previous-trial effects) only if the response was also repeated across trials. ERP-wise, however, perceptual previous-trial effects (on N2pc latencies) were evident also in trials in which only the target dimension, but not the response was repeated, resulting in no behaviourally measurable effect.

However, behaviourally, the mean RT redundancy gains in the present Experiment 3 (± 28.9 ms) using a constant-identity target were exactly of the same magnitude as the ones observed in Töllner et al.'s (2010) experiment (± 29.0 ms). The N2pc latency redundancy gains were slightly, but consistently enlarged in the present Experiment 3 compared to Töllner et al.'s effect (± 11.5 ms for redundant compared to single colour signals, ± 10.9 ms for redundant compared to single orientation signals /

mean: ± 11.2 ms). It seems that the frequent changes of the context may require a larger contribution of the (active) pre-attentive switching processes.

In summary, the findings of the present Experiment 3 rule out the V1 hypothesis that the redundant-signals effect is based on feature-based processing in V1 (Koene & Zhaoping, 2007; Li, 2002). They suggest that in feature search for known target features observers do not automatically adopt a feature search strategy (Bacon & Egeth, 1994), rather, they seem to base search on dimensional saliency signals (Müller et al., 1995). The redundant signals effect and co-active processing of redundant signals was shown to arise at the level of dimension-based saliency activations (Krummenacher et al., 2001, 2002) prior to focal-attentional target selection (Töllner et al., 2010). On the basis of the present data, however, a possible contribution of later post-selective stages (target identity processing and response-selection [stimulus-locked LRP], but not response-execution stages [response-locked LRP]) to the generation of the redundant signals effect cannot completely be ruled out. Finally, the observed RT redundant signals effect (behaviourally as well as ERP-wise) in the present Experiment 3 using a constant target identity is very similar to those found by Töllner et al. (2010) using a variable target identity across trials. However, electro-physiologically, the N2pc latency redundant signals effect seemed to be somewhat more pronounced for constant relative to variable target identities. Still, it can be concluded, that the generation mechanisms of the redundant signals effect are very similar in both paradigms.

5. Top-down weighting of dimensions

In the framework of the Dimension Weighting (DW) account (Müller, Heller & Ziegler, 1995; Müller, Reimann & Krummenacher, 2003; Krummenacher & Müller, 2005) pre-attentive processes are modulated by (bottom-up) adjustments of dimensional weight settings given rise to by previous-trial and redundant signals effects enhancing focal attentional target selection. As the early perceptual stage of selective processing is generally thought to be modulable in nature by Müller and colleagues, this also holds true for potential implicit or explicit top-down processes (such as observers' goals) that are assumed to accelerate target selection.

The assumption that early perceptual component processes of selection are susceptible to top-down modulation is in marked contrast to the claims of a group of other researchers. The theoretical position challenging the possibility that early processes can be modulated is voiced most prominently by Theeuwes and colleagues (e.g., Mortier, Theeuwes & Starreveld, 2005; Mortier, van Zoest, Meeter & Theeuwes, 2007; Theeuwes, 1992, 2004; Theeuwes, Atchley & Kramer, 2000; Theeuwes, Reimann & Mortier, 2006), but also others such as Kristjánsson, Wang and Nakayama (2002) and Maljkovic and Nakayama (1994) who do not accept the possibility of modulations of the processing stages prior to attentional selection. According to their point of view, early perception is completely automatic in nature and exclusively driven by (bottom-up) stimulus properties and/or salience activation. For instance previous-trial effects are referred to as passive inter-trial priming (Maljkovic and Nakayama, 1994) rather than implicit weighting effects (Müller et al., 1995, 2003). The redundant signals effect, as discussed in Chapter 4.2, is described as co-activation of response-decisions at the post-selective level of processing (Feintuch & Cohen, 2002) rather than co-activation of dimension-based saliency activations at pre-attentive processing stages. Some of the researchers mentioned above prefer to explain their findings in the framework of post-selective response-related models such as the Dimension Action (DA) model (Cohen & Shoup, 1997, 2000).

Note, however, that some pure salience-based models of selection (Itti, 2006; Li, 1999) also argue that their models are simply a "coarse approximation" (Itti, 2006, p. 962) of human attention or an "idealisation when top-down influences are not effective" (Li & Snowden, 2006, p.912). That is, (at least) implicitly, these authors acknowledge the existence of an additional (top-down) factor as a powerful modulator of basic stimulus-driven attentional selection.

A word about terminology is required here: In the framework of the DW model (Müller et al., 1995) that is at ease with the concept of modulable pre-attentive processing stages, the term "bottom-up modulation" refers to modulations of signals at pre-attentive stages that are based on stimulus properties, but rather than being exclusively driven by stimulus saliencies, they represent weighted saliency activations. By contrast, accounts claiming the pre-attentive stage to be impenetrable to any

kind of modulation (bottom-up or top-down) the term bottom-up is used for stimulus-driven processing which clearly is purely automatic. Bottom-up processing is therefore also referred to as exogenous selection (Posner et al., 1980).
The term top-down describes any additional process that comes into play during the whole process of target detection, i.e. any process not based on stimulus properties. This includes explicit knowledge about e.g. the target's identity that supports to the observer's goals and intentions to meet the task demands to detect the target as quickly and accurately as possible. Top-down processing is therefore also referred to as endogenous selection and it does not specify whether the endogenous effects are consciously represented (i.e., can be reported) or not by an observer.

Importantly, the debate about modulability of early processes is still vivid (for detailed discussions of the pre-selective position, see Müller et al. 2006, 2010; of the post-selective position, see Theeuwes, 2010; for a recent integrative review see Kristjánsson et al., 2010) – empirical evidence was found for both perspectives.

In the following, modulation of (assumedly automatic) previous-trial effects (5.1) and the framework of the attentional capture paradigm (5.2) are discussed in order to provide evidence for bottom-up and top-down control of early visual processing. At the end of the chapter, empirical results that contribute to the debate are presented.

5.1 Automatic inter-trial priming versus weighted dimension-based inter-trial effects

Maljkovic and Nakayama (1994), in a compound search task, presented participants with colour singleton targets. Target and the distractors swapped colours (green or red) unpredictably across trials; all stimuli were diamond-shaped with the left or right corner of the diamond cut off (see also Bravo & Nakayama, 1992). The task of the observers was to first detect the target and to then indicate, as quickly as possible, on which side of the target item the cut off was located; in other words, they used a compound task (Duncan 1985; see Section 4.1 for a detailed description of the task). Maljkovic and Nakayama (1994) found inter-trial effects in such a way that RTs were speeded when the target defining feature was repeated across trials compared to when it was changed. The crucial point is that in their Experiment 2 the target identity was 100% predictable – it changed in each successive trial – but the RT costs for switch trials were not abolished or reduced compared to a condition in which the target never changed across trials. Although participants were perfectly able to fully prepare themselves for the upcoming target colour (red or green) they were not able to overcome the passive priming by the target definition of the previous trial. Maljkovic and Nakayama (1994) therefore concluded that target detection is based on passive implicit short-term memory which cannot be

accessed by cognitive processes and, that stimulus expectancies (probabilities of target feature change of 70% or 90%) or complete pre-knowledge (100% target change predictability) do not modulate previous-trial effects.

Hillstrom (2000) used a design that was very similar to that of Maljkovic and Nakayama (1994); stimuli were pink and purple bars (the colours swapped between the target and the distractors across trials) that were either vertically oriented or tilted to the left. Participants' task was to detect the target and to report its orientation. In her Experiment 1 she tested alternating sequences in which the target changed colour every second trial (following the AABBAABB … pattern) versus random sequences in which the target colour of the next target was completely unpredictable for the participants. Results revealed significant previous-trial effects in both conditions, but the effects were clearly modulated in such a way, that "[r]esponses were 115 ms faster, on average, to trials in the alternating sequences than to trials in the random sequences [...], a result that reflects expectancy. Sequence also influenced the size of the defining-feature repetition effect [...]: The defining-feature repetition effect was larger for the alternating sequence (132 ms) than for the random sequence (78 ms), …" (Hillstrom, 2000, p. 803).

Müller, Krummenacher and Heller (2004) came to a similar conclusion in a series of experiments. First, they showed that implicit memory was sufficient for producing inter-trial facilitation in a simple feature search. When (surprisingly) asked about the target's identity, observers failed to report it and proved to have no explicit memory of the target identity (although some other target properties such as its location could be reported with near perfect accuracy). More important, they also demonstrated that explicit memory instruction clearly modulate previous-trial effects; when participants were asked to encode the critical target defining dimension or feature, inter-trial facilitation was enhanced (note that the enhancement was dimension-specific, even when the target feature was to encode). Finally, the increased inter-trial effects were identified as being caused by the active maintenance of the target properties in memory during the inter-trial interval, rather than by an additional time requirement to determine the target's identity. Therefore they concluded that implicit memory is sufficient for the generation of dimension-based inter-trial effects, but that they are subject to modulations by explicit memory effects.

Another method to investigate top-down modulations of previous-trial effects was used by Müller, Reimann and Krummenacher (2003). They investigated the ability of observers to set themselves for the upcoming target identity by pre-cueing the relevant target dimension on a trial-by-trial basis. A symbolic cue (the word "colour" or "orientation") indicated the likely target dimension with a validity of 80% (Experiment 1) or 100% (Experiment 2). Results revealed dimension-specific cueing-benefits and -costs for valid and invalid cues, respectively, compared to a neutral cueing condition (indicated by the word "neutral"). More importantly, the dimension-specific inter-trial effects were significantly

reduced (though not completely abolished) in pre-cued (valid and invalid) trials compared to neutral conditions. Importantly, under neutral cueing conditions, responses to repeated target dimensions were expedited compared to when the target dimension changed across trials, a result that replicates RT patterns of dimension-based inter-trial effects reported in earlier work (Found & Müller, 1996). Furthermore, Müller et al. (2003) demonstrated that the cueing effects are dimensional in nature. If the exact target feature (instead of the dimension) was cued (e.g., with the words "red" or "left-tilted"), observers used the feature information to set themselves for the upcoming target dimension rather than the upcoming feature. As an example, participants benefited from a cue indicating "red" as the upcoming target feature in trials with a blue target as well (Experiment 3). This pattern of results was seen also for features that were presented infrequently (e.g., a yellow target; Experiment 4). There was, if any, only little evidence for additional feature-based cueing effects, and these were observed only for features of the colour dimension. With (semantic) feature cues, observers seemed to be able to set themselves for a specific colour feature, rather than for the more general colour dimension. (The finding is similar to the feature-specific repetition effect revealed by Found and Müller, 1996 and by Töllner et al., 2008. For a discussion of the effect, see Chapter 4.1.)

Taken together, in terms of DW (Müller et al., 1995), Müller, Reimann and Krummenacher (2003; see also Müller, Krummenacher & Heller, 2004) stated that "the dimensional weight settings – and, by implication, the inter-trial facilitation – can also be influenced by expectation-based processes; that is, attentional weight can be actively shifted to a dimension" (Müller et al., 2003, p. 1031). Although inter-trial effects are mainly based on some kind of pre-attentive implicit visual short-term memory, this memory and therefore the magnitude of inter-trial effects can be modulated by explicit top-down processes that set the system for feature saliency analyses within the relevant dimension. Consequently, inter-trial effects are not purely automatic in nature; rather they are susceptible to top-down modulations or to top-down control, at least to some extent.

Müller et al.'s conclusion was strengthened by a set of other findings revealing top-down modulation of inter-trial effects in cueing experiments (e.g., Fecteau, 2007; Leonard & Egeth, 2008; see also Wolfe, Horowitz, Kenner, Hyle & Vasan, 2004). As an example, Fecteau (2007) presented displays containing a shape and a colour singleton. Only one of the singletons was relevant for the task. By pre-cueing either the shape or the colour singleton, observers were informed, at the beginning, of each trial about the to-be-attended singleton. Performance was only facilitated by repetitions of colour or shape when colour or shape, respectively, was relevant to the observer's current goals (namely, to report about the relevant singleton). If the repeated feature possessed by the target was irrelevant (un-cued), all evidence of previous-trial effects was abolished.

By contrast, Theeuwes, Reimann and Mortier (2006) replicated dimensional cueing effects in a simple feature search (Experiment 1). Observers had to detect a singleton defined in the colour (red circle amongst green distractor circles) or shape dimension (green diamond amongst green distractor circles).

A symbolic cue (presentation of the words “colour”, “shape” or “equal” as the neutral cue) indicated the upcoming target dimension with a probability of 83% on a trial-by-trial basis. RTs in validly cued trials were decreased and RTs in invalidly cued trials were increased relative to neutrally cued trials suggesting improvement of visual search due to top-down knowledge. Additionally, Theeuwes et al. also observed inter-trial effects that were independent of cue validity; a finding that is in contrast to the results of Müller et al. (2003). In a second experiment, Theeuwes et al. (2006, Experiment 2) did not find dimensional cueing effects in a compound task using exactly the same cues and stimuli as in Experiment 1, but with the additional task to report the orientation of a line within the target singleton (see Section 4.1 for a detailed description of the task). Mean RTs to the valid and the neutral cue condition were equal and mean RTs for invalid cued trials were only non-significantly increased (by about 4 ms). Since the only difference between the two tasks (detection and compound) was the additional response requirement, Theeuwes et al. concluded that the dimensional cueing effect in both tasks must arise at the response selection stage (as proposed by Cohen & Magen, 1999, in the Dimension Action model). Additionally, in the compound task, substantial previous-trial effects were revealed for target dimension switch versus repetition trials, a finding that supports the assumption that pre-attentive processing was the same in both tasks, and that pre-attentive mechanisms were not affected by the top-down set as the inter-trial effects were not modulated by the cueing. It should be noted, though, that the magnitude of the previous-trial effects in the compound task was less pronounced (10 ms) compared to the magnitude of the effect in the simple detections task (34 ms). Müller and Krummenacher (2006) accounted for these reduced inter-trial effects in the compound relative to the simple detection task by arguing that there seems to be a link between stimulus and response expectancies (see Chapter 4.1 of the present thesis). The lack of an overall cueing effect in the compound task was addressed by Müller and Krummenacher (2006) by replicating the tasks of Theeuwes et al. (2006). While Müller et al. used the same stimuli as Theeuwes et al. (2006) they attempted to actively increase the observers’ incentive to actively use the information of the cue. They reasoned that in Theeuwes’ (2006) experiment, because of the uselessness of the information of the cue as to the actual response, observers might have not (consistently) set themselves to the cued dimension, rather they simply waited for the singleton feature target to pop out of the display. Therefore, in Müller et al.’s experiment, participants were informed as to the validity of the cue (80%) and they were instructed to make use of the cue. At the end of each experimental block, observers had to indicate how well they had set themselves to the dimension indicated by the cue. On a scale from 0 (did not use the cue) to 3 (consistently used the cue), the mean rating was 2.4. The behavioural results revealed small, but statistically significant symbolic cueing RT benefits (of 6 ms) and costs (of 5 ms) in valid and invalid cued trials, respectively, relative to the neutral cue condition.

In line with Müller and Krummenacher’s (2006) findings, cueing effects in compound tasks were recently reported by Leonard and Egeth (2008), who used stimuli similar to the ones used by

Maljkovic and Nakayama (1994). The target diamond was either red or green (and swapped colour with the distractors), and the side of the cut off corner had to be reported. Participants were prepared with symbolic cues (words: “red”, “green” or “either”) and cue validity was at 100%. Leonard and Egeth (2008) revealed substantial cueing effects (costs/benefits for validly/invalidly cued relative to neutrally cued trials). However, they also showed that the benefit of target foreknowledge decreased with increasing number of homogeneous distractors (set sizes: 3, 5, 7 items). Leonard and Egeth (2008) hypothesised that, adapting their argument from Meeter and Olivers’ (2006) ambiguity theory, adding homogeneous distractors to the display decreases the ambiguity as to the target’s identity. Decreasing the ambiguity might eliminate the beneficial (but now useless) effects of a cue. They further reasoned that set size and reduced ambiguity might explain the difference in findings compared to Theeuwes et al. (2006). Theeuwes et al. had used a set size of nine stimuli; consequently, cueing effects might have been too small to become statistically significant.
However, one could also argue, following the reasoning of Müller and Krummenacher (2006) that, as cue validity in the Leonard and Egeth (2006) study was 100%, the incentive for observers to use the cue information to facilitate search was (near) perfect. In Theeuwes et al.’s (2006) paradigm, however, the cue was only valid in 83% of the cases. Participants must have been suspicious, to a certain degree, as to the helpfulness of the information of the cue; they might have wanted to avoid getting trapped and respond erroneously in invalid cue trials.

Recently, Töllner, Zehetleitner, Gramann and Müller (2010) investigated previous-trial and cueing effects by means of event-related potentials (ERPs) in a compound task. The stimuli were identical to the ones used by Töllner et al. (2008); targets were red circles (colour singleton) or yellow squares (shape singleton) presented amongst yellow circles. The observers’ task was to report the line grating (horizontal, vertical) within the stimuli. Each trial was semantically pre-cued by the word “colour”, “orientation” or “neutral” and cue validity was 80%. Behaviourally, Töllner et al. (2010) replicated earlier results of cueing and previous-trial effects under compound conditions (Müller and Krummenacher, 2006; Müller et al., 2003; Töllner et al., 2008). Results revealed significant cueing effects; though mean RT differences to invalidly compared to neutrally cued trials were only marginally significant, the over all ‘costs-plus-benefits’ cueing effect was substantial. Importantly, across trials observers only benefited from dimension repetition relative to change trials when the response was repeated as well (same dimension, same response [sDsR] vs. different dimension, same response [dDsR]). If the response changed across trials, dimensional previous-trial effects were abolished (same dimension, different response [sDsR] vs. different dimension, different response [dDdR]). ERP-wise, the N2pc to targets defined in the cued dimension was found to be more pronounced (amplitude) and to peak earlier compared to the N2pc to targets defined in the non-cued dimension; the effect was statistically substantial. For neutrally cued trials, the N2pc amplitude as well as the N2pc latency was in between the valid and invalid condition (and not significantly different

from either of them). That is, the speed of pre-attentive processing was found to be modulated by cue validity, in other words, by participants' top-down sets. Interestingly, no significant effect of cue validity was observed in the stimulus- as well as in the response-locked LRPs, a result that suggests that top-down control has no effect on response-selection and -execution stages. However, similarly to the results of Töllner et al. (2010) and Experiment 3 of the thesis, the stimulus-locked LRP latency for targets defined in the cued dimension was accelerated (though not markedly). Stated more generally, the stimulus-locked latency was fastest for the condition which was processed fastest at the level of the N2pc. For the inter-trial effects, again, as in the Töllner et al. (2008) study, irrespective of the (motor) response, dimension changes were reflected in shortened latencies and enhanced amplitudes of the perceptual selective component, the N2pc only. Irrespective of dimension changes, motor response changes were accompanied by enhanced amplitudes of the response-related component, the response-locked LRP only.

Note that neither Töllner et al. (2010) nor Müller and Krummenacher (2006) replicated the interaction between cue validity and inter-trial effects (reduction of the cross-dimensional RT-costs in valid and invalid relative to neutral cued trials) found by Müller et al. (2003). Töllner et al. (2010) suggest that this might be caused by the random presentation of cue conditions they had used in contrast to the blocked presentation of the neutral cue condition in the Müller et al. (2003) study. They suggest that only a block-wise presentation of neutrally cued trials would serve as a proper baseline for valid and invalid cueing effects, because only under the blocked condition stimulus-dependent previous-trial effects are observable in a pure manner (under the assumption, that participants maximally use the neutral cue as a temporal warning signal). If (rare) neutral cues are presented randomly within (frequent) informative cues on the other hand, observers might carry over a strategy to top-down set themselves to one of the target dimensions in the case a neutral cue is presented (for example preparing for the dimension they simply find easier to prepare).

To conclude, there is evidence from behavioural (Fecteau, 2007; Hillstrom, 2000; Leonard and Egeth, 2008; Müller et al., 2003, 2004, 2006) as well as electrophysiological (Töllner et al., 2010) studies suggesting that previous-trial effects arise at the pre-attentive processing stage and that they are modulable by observer's top-down sets.

5.2 Attentional capture

In order to test to what extent selection is bottom-up or top-down controlled, a paradigm in which both processes compete against each other is used: The attentional capture paradigm (Theeuwes, 1991, 1992, 1994). Typically, in attention capture tasks, observers have to detect a salient singleton target and report its presence, absence or another response-relevant feature (compound task), in addition they are simultaneously with the presentation of the target distracted by the presentation of another, task irrelevant, but highly salient singleton item (that, by instruction, they have to ignore).
Consequently, three conditions have to be tested in order to measure whether possible top-down mechanisms influence the pre-attentive processing (speed) of the target selection or whether initial perception was purely stimulus-driven (automatic). First, the search task has to allow for a parallel, pre-attentive search; second, the features of the distractor item have to be completely task-irrelevant (no incentive for observers to attend them); and, third, observers have to have a clear task goal (fast and accurate search for a target).
The degree to which the singleton distractor interferes with the search for the task-relevant target shows to what amount attention was captured by the task-irrelevant item and thus to what extent stimulus-driven (automatic allocation of the attention focus to the most salient item in the display, the distractor) or top-down controlled (guided allocation of the attention focus to the task-relevant item in the display) processes contribute to pre-attentive perception. The amount of distractor interference (stimulus-driven capture versus contingent capture) can be and was measured by RTs (Bacon & Egeth, 1994; Folk & Remington, 1998; Folk, Remington & Johnston, 1992; Folk, Remington & Wright, 1994; Leber & Egeth, 2006; Müller, Geyer, Zehetleitner & Krummenacher, 2009; Schreij, Owens & Theeuwes, 2008; Schreij, Theeuwes & Olivers, 2010; Theeuwes, 1991, 1992, 1994, 1996, 2004; Theeuwes, Atchley & Kramer, 2000; Theeuwes, Kramer & Belopolsky, 2004; Theeuwes & Van der Burg, 2008; see also Jonides & Yantis, 1988; Yantis & Egeth, 1999; Belopolsky, Zwaan, Theeuwes & Kramer, 2007; for comparable results though not revealed in a ‘classical’ capture design), error rates (Theeuwes, Kramer & Kingstone, 2004), saccade latencies and destinations (Geyer, Müller & Krummenacher, 2008; Godijn & Theeuwes, 2002; Theeuwes, de Vries & Godijn, 2003) and elicitation of the attention-specific ERP component N2pc (Eimer & Kiss, 2008; Hickey, McDonald & Theeuwes, 2006; Kiss, Jolicoeur, DellAcqua & Eimer, 2008).

The initial experiments, introducing the ‘irrelevant singleton’ paradigm to visual search, were conducted by Theeuwes (Theeuwes, 1991, 1992, 1994). Theeuwes used a compound task (Duncan, 1985); stimuli were coloured diamonds and circles arranged on an imaginary circle with lines of different orientations presented within the search stimuli. In the shape search condition, participants had to search for a shape target (e.g., a green circle among green diamonds), but in some trials simultaneously with the onset of the target and non-target items, an odd coloured distractor was

presented (red diamond). (One of the non-targets was replaced by a distractor.) In the colour condition, participants searched for a colour target (e.g. a green circle among red circles) and in some trials an odd shaped distractor (red diamond) was presented, as well. Participants' task was to report the orientation of the line within the target item. Theeuwes (1992) found RTs to be significantly slowed in the shape condition when a colour distractor was present compared to when no colour distractor was present. This result suggests that attention must have been captured automatically by the most salient item in the display, the colour distractor. In the colour search condition, the shape distractor failed to capture attention and RTs in the distractor present and absent conditions were equal because the most salient item in the display was the colour target. Theeuwes reasoned that participants, although completely informed about the irrelevance of the singleton distractor (top-down set), failed to ignore it, if it was more salient (colour singleton) than the target (shape singleton).

Bacon and Egeth (1994) challenged Theeuwes' (1991, 1992) purely stimulus-driven interpretation of irrelevant distractor effects. Bacon et al. first replicated Theeuwes' (1992) results of attentional capture by an irrelevant singleton (Experiment 1). In a second experiment, they added additional shapes (i.e. squares and triangles) to the display to vary the 'number of unique forms'. There were either zero (only non-targets, green diamonds), one (the target, always the green circle), two (the target + one odd shaped green non-target [either a square or a triangle]) or three (the target + two odd shaped green non-targets [a square and a triangle]) unique shapes in the display. Participants had to respond according to the orientation of the line inside the target item. In distractor-present trials one of the diamond-shaped non-targets was oddly coloured (the additional odd-shaped non-targets were never the distractors). Compared to the original condition in which the shape singleton was always unique and RTs increased with presence of the singleton distractor, in Bacon and Egeth's (1994) Experiment 2, in which distractors were variable and heterogeneous, attention was not captured by the oddly coloured distractor. Note that search slopes independent of the number of unique forms were greater than zero, but below 10 ms / item, indicating a parallel pre-attentive search had taken place irrespective of the heterogeneity of the distractors (Duncan & Humphreys, 1989). According to Bacon and Egeth (1994) the modulation of the capture rate was caused by two different search modes participants had adopted in the respective tasks. In the irrelevant singleton conditions, observers relied on difference signal detection, they adopted a 'singleton search mode'; the target was detected on the basis of its salience signal. In the heterogeneous distractor paradigm, observers are thought to switch search strategy to a 'feature search mode'. Due to the heterogeneous display with more than one feature difference in the display, participants cannot rely on salience signals; rather, they create a top-down set in order to search exclusively for unique target feature (circle). Attention is therefore always directed to the relevant feature and irrelevant singletons no longer interfere with search. Bacon and Egeth (1994) concluded that under certain conditions (feature search mode) "goal-directed selection of a specific known feature singleton identity may override stimulus-driven capture by salient singletons"

(Bacon & Egeth, 1994, p. 493) and, as the search strategy, is chosen voluntarily. Selection can be described as being modulable by top-down processes.
However, recall that in Experiment 3 of the present thesis, it was shown, that even if participants are enabled to choose a feature search mode, they seem to prefer to rely on a singleton search mode, at least in some variants of feature search tasks.

Theeuwes (2004) responded to the challenge from Bacon and Egeth (1994) by claiming, that the modulation in the Bacon and Egeth (1994) study was caused by the heterogeneity of the display (search was more focussed, regardless of the not to steep search functions) rather than the top-down sets of the observers. Theeuwes (2004) used three different shape singletons (and thus forced participants to a feature search mode) as well, but simply increased the set size, thereby increasing the distractor and target salience. In detail, he presented the target (a diamond) and two shape singletons (a square and a triangle) amongst non-targets (circles), in addition he increased the number of non-targets in the display. In distractor-present trials, one of the circular non-targets changed its colour. Compared to Bacon and Egeth (1994), who used set sizes of 5, 7 and 9 items, Theeuwes compared displays containing 12 or 20 items (flat search functions were revealed) with displays containing 5 or 9 items (steep search functions with slopes of 11 - 13 ms / item were revealed). Attention was captured only in the parallel pre-attentive search (set size 12, 20) and was not in the serial search condition (set size 5, 9). Theeuwes (2004) concluded, that “attentional capture cannot be eliminated without producing a search slope” (p. 68).

The exact opposite view to Theeuwes’ stimulus-driven attentional capture account (Theeuwes, 1991, 1992) assuming that attention is always captured in a bottom-up fashion is the ‘contingent capture hypothesis’ of Folk and colleagues (Folk et al., 1992, 1994, 1998). The contingent capture hypothesis claims that only features that are relevant to the current ‘attentional set’ of the observer are able to capture attention. Even a very salient feature is not assumed to capture attention if it does not match the observer’s attentional set. That is, if an observer is looking for red, only red items will capture attention; any other feature, for example an onset will fail to capture attention. In their initial experiments Folk et al. (1992) tested observers with a spatial cueing paradigm in which a cue display was rapidly followed by a target display. Both displays contained four spatially identically organised squares (top, bottom, left, right) plus a central fixation square. Participants had to either search for a target (a letter ‘X’ or a ‘=’ sign) defined by colour (red item amongst white distractors) or an onset (a single white onset target abruptly appearing without distractors) appearing randomly in one of the four outer squares and their tasks was to discriminate the target’s identity (‘X’ or ‘=’). The valid and invalid cue conditions were presented block-wise and the cue was always 100% predictive as to the target’s location; in valid trials, the target appeared always at the cued location, in invalid trials, the target never appeared at the cued location but at any other of the remaining three locations. Cue

displays either contained a colour cue (one of the squares was surrounded by four red circles, one on each side of the square, the other squares were surrounded by white circles instead) or an onset cue (one of the squares only was surrounded by white circles; all the other squares were not marked). All conditions (colour or onset target with colour or onset cue) were varied in a factorial design.
The most important finding of Folk et al.'s (1992) study was, that spatial cueing effects (relatively faster RTs when the cue and the target were presented at the same location and relatively slower RTs when the locations of cue and target were not identical) were observed only, if a cue matched the current task set. If observers were set to search for a colour target, cueing effects were only observed, if the cue was a colour cue; RTs to same or different cue and target locations were equal if the cue was an onset cue. The other way round, if observers were set to search for an onset target, cueing effects were only observed if the cue was an onset cue; if the cue was a colour cue, RTs between same and different locations of the target and the cue did not differ. This finding suggests that top-down attentional set determined the effectiveness of the cue. Only items that matched the attentional set were captured, items that did not match the attentional set were ignored.

The findings of Folk et al. (1992) were replicated several times using various modifications of the initial paradigm described above (e.g., Eimer & Kiss, 2008; Folk et al., 1994, 1998; Folk & Remington, 2006; Remington, Folk & McLean, 2001).
Eimer and Kiss (2008), in an EEG study, used the N2pc as an indicator of spatially selective attentional processing in an attempt to investigate the manipulation of task set on attentional capture. Eimer et al. (2008) used a spatial cueing paradigm similar to the one used by Folk et al. (1992). In contrast to Folk et al., Eimer et al. made the cue spatially non-predictive as to the location of the upcoming target across trials. In the colour task participants had to report the orientation (vertical, horizontal) of a red target bar shown among grey non-target bars; in the onset task, the orientation of a single grey target bar had to be discriminated. In both tasks, target displays were pre-cued by colour cues: sets of small dots arranged at six locations on an imaginary circle. One of the sets was red, the others grey. Behaviourally, and analogous to the results of Folk et al. (1992) spatial cueing-benefits (cue and target at the same location) and -costs (cue and target at different locations) were only revealed in the colour task indicating that attention was captured by the colour cue. In the onset task, in which colour singletons were irrelevant for the current attentional set, no cueing-benefits (or -costs) were observed. RTs to the target were equally fast no matter whether the location was pre-cued (by the colour cue) or not. Additionally, with respect to the cue display, Eimer et al. found that the N2pc was elicited in the colour task only; no N2pc component was evident in the onset task. The authors concluded that although spatially uninformative, the colour cue captured attention when colour was the attentional set of observers, but did not, when onset was the attentional set. If the colour cue would have captured attention in a bottom-up fashion and irrespective of task set in the colour as well as in the onset condition, an N2pc to the colour cue should have been observed.

Belopolsky et al. (2010), in a recent study, used Folk et al.' (1992) spatial cueing paradigm, but instead of presenting the relevant target block-wise (as in Folk et al.'s, 1992, experiment) the authors encouraged participants to adopt a top-down set on a trial-by-trial basis. In a series of experiments Belopolsky et al. found attentional spatial cueing effects for both task sets and both cue types; that is, attention was captured irrespective of the attentional set of the observers. In the case of a top-down set for colour targets, participants were equally captured by both, colour and onset, cues. The same result was found for the top-down set for onset targets. Belopolsky et al. (2010) used exactly the same design as Folk et al. (1992) in the original study, with the exception that, prior to the spatial cueing display an instructional cue was presented. The critical point is that the cue indicated whether participants should look for a colour (indicated with RED) or an onset (indicated with WHITE) target in the subsequent trial.

That is, in fact, participants were instructed to search for one out of two features (red or white) of one dimension (colour). It might be possible, that, in line with the DW account (Müller et al., 1995; Müller et al. 2003) according to the cues (red, white) the dimensional weight setting for colour was up-modulated and facilitated search (and therefore capture) of both colour features. In other words, participants might have adopted one single attentional set for colour, including red and white features, instead of creating two attentional sets, one for colour and one for onset. Two attentional sets are a pre-requisite for tests of the influence of an attentional task set on a relevant versus an irrelevant feature cue. If participants would have been cued to search for colour (symbolic cue colour instead of red) or onset (symbolic cue onset instead of white), participants might have adopted two different attentional sets and attentional capture, in terms of the contingent capture hypothesis (Folk et al., 1992), would have been modulated on a trial-by-trial basis as well.

Support for the above alternative interpretation of Belopolsky et al.'s results comes from Kiss et al. (2008). Participants' in their experiments had to detect a predefined target (a red circle amongst green circles in the colour task or a green diamond amongst green circles in the shape task) and to report whether the target was presented to the left or the right side of the fixation cross, respectively. They found a large N2pc to colour and shape targets, indicating attentional capture of the singleton stimuli that matched the current task set. However, they also found well pronounced N2pc components to non-target singletons that were defined in the target dimension as well (blue circles in the colour condition and green squares in the shape condition), although they were not defined in the exact target feature (red or diamond-shaped). If task-set contingent capture would operate only on a featural basis as postulated by the strong version of the paradigm (Folk et al., 1992), no such N2pc to targets defined in the target dimension, but not by the target feature should have been elicited. Therefore, it is highly likely, that Belopolsky et al. (2010) with their cue (red or white) created an attentional set for colour only and therefore the onset target was not treated as an onset, but as another colour target. In this case, it is evident why they did not find a modulation of the attentional capture as predicted by the contingent capture hypothesis. Note that in the Kiss et al. (2008) study, no N2pc to irrelevant

dimension singletons was elicited, which is further support for a top-down modulation of attentional capture that is contingent on the current target dimension. Consequently, this finding provides further evidence against a purely stimulus-driven pre-attentive processing.
However, in their Experiment 3, Kiss et al. (2010) presented task-irrelevant and task-relevant singletons simultaneously at the opposite sides of the search array and revealed N2pcs to be elicited contralateral to the targets and not to the distractors. They therefore showed, that even in highly competitive situations participants followed the top-down set and attended the target and successfully ignored the task-irrelevant distractor. This finding stands in marked contrast to the results of Hickey et al. (2006) who had found the distractors as well as the targets to produce strong N2pcs in exactly the same display-setting (oppositional presentation of the target and the distractor). Crucially, the distractor-N2pc was elicited first and the target-N2pc followed. They interpreted this as a bottom-up effect in terms of an attention shift from the more salient distractor to the task-relevant target.

In a series of experiments, the top-down modulation of attentional capture was addressed in paradigms that differ from the spatial cueing paradigm of Folk et al. (1992). By means of Theeuwes' (1992) paradigm Geyer et al. (2008) and Müller et al. (2009) found evidence for a top-down modulation of attentional capture by salient distractors; that is, evidence against automatic processing on the pre-attentive stage. Geyer et al. (2008) and Müller et al. (2009) argued that the interference of the distractors can be reduced by the acquisition of a proper top-down strategy to inhibit the distractor (to down-modulate the weight for the distractor dimension or up-modulate the weight for the target dimension) and that such a suppression strategy would only be developed if the incentive to use it was large enough. Therefore, in a series of experiments they systematically varied the distractor display probability across trials. Experimental blocks contained 80%, 50% or 20% of distractor trials. All participants started the experiment with a pure block, either always (100% distractor probability) or never (0% distractor probability) containing a distractor. The rationale behind the procedure was that participants, according to their initial distractor experience, would be provided with different top-down sets. This is in accordance to Leber and Egeth (2006), who had shown that extensive training resulted in top-down control over attentional capture. Participants in the Leber and Egeth (2006) experiment were expected to carry over attentional strategy sets from the practice to the experimental blocks. Participants that were initially presented with a distractor in each trial (100% distractor probability) would be provided with a big incentive to develop a strategy to inhibit the distractor and with the possibility to train this strategy from the beginning of the experiment. Under the assumption that the incentive to suppress the distractor was only given if the cost of not suppressing the distractor is high overall, it was expected, that in subsequent blocks with decreasing distractor probability (50%, 20%) distractor interference would increase again. On the other hand, participants initially being presented with no distractor trials, due to the lack of distractor experience, were expected to show maximal distractor interference with the subsequent 20% distractor trials condition, but would later, with

increasing distractor probability (50%, 80%), be provided with an incentive to develop a distractor inhibition strategy and to successfully apply it.

In line with the predictions, results revealed markedly decreased capture RT-costs (Geyer et al., 2008; Müller et al., 2009), decreased capture saccade latency-costs and a decreased proportion of initial saccades toward the singleton distractor (Geyer et al., 2008) in experimental blocks with high compared to low distractor probability (80% versus 20%). This was true for both groups of observers, participants who had started the experiment with the 100% or the 0% distractor condition, though the capture effect in the 20% condition was more pronounced for participants who had started with the 0% condition, as hypothesised.

In conclusion, participants who had started the experiment with a 100% block used a well trained top-down strategy from the beginning of the experiment. As the incentive to use the strategy decreased (with decreasing distractor probability) the capture effect increased. Participants who had started the experiment with the 0% distractor condition were captured by the distractor to a higher degree relative to participants of the 100% distractor condition in the 20% distractor probability blocks. But as the incentive to inhibit the distractor increased (with increasing distractor probability) they developed a top-down strategy aiming to prevent attention from being captured.

Finally, all participants were able to actively up-modulate the weight of the target dimension or to down-modulate the weight of the distractor dimension. The dimension-based saliency signal at the level of the priority map was therefore enhanced for the target and attenuated for the distractor, so that the target was more likely to win the competition for focal attention (as the basis for a fast report of the task-relevant feature of the target).

Experiment 4: Modulated attentional capture by onset distractors

Purpose of the present study

In the present experiment the modulation of attentional capture aimed to be replicated under a special capture condition, namely the attentional capture by onset distractors. In several experiments, onsets have been shown to strongly capture attention (e.g., Jonides & Yantis, 1988; Yantis & Jonides, 1990; Yantis & Egeth, 1999). Jonides and Yantis (1988) claimed that onset stimuli capture attention purely automatically, in contrast to, for example, colour or luminance defined stimuli (see also Yantis and Hillstrom, 1994; Franconeri, Hollingworth & Simons, 2005). Recently Schreij, Owens and Theeuwes (2008; see also Schreij, Theeuwes and Olivers, 2010) used the spatial cueing paradigm of Folk et al. (1992) and showed, that even when observers adopt a top-down set for colour (the target was a red character amongst white distractor characters), an irrelevant new object presented with an abrupt onset captured attention. They concluded that abrupt onset overrides top-down sets for colour.

Overview of Experiment 4

The paradigm of Geyer et al. (2008) and Müller et al. (2009) was applied, but in the present task a highly salient onset distractor (OD) was used. The OD display probability was systematically varied across blocks. Again, half of the participants started the experiment with a 100% OD condition in order to provide them initially with a high incentive to develop an OD suppression strategy and the possibility to learn this strategy. As in subsequent blocks the OD display probability decreased continuously (80%, 50% or 20% of the trials contained ODs) participants were expected to decrease in their OD inhibition performance due to decreasing incentive to suppress an infrequent OD. The other half of the observers began the experiment with a 0% OD condition. As in subsequent blocks the OD display probability increased continuously (20%, 50% or 80% of the trials contained ODs) participants were expected to improve in their OD inhibition performance due to increasing incentive to suppress an OD appearing frequently.

Note that with this task it becomes not entirely clear, whether attentional capture was top-down (incentive of the observers) or bottom-up (statistical learning of distractor probability) modulated or both. Statistical learning refers to the capability of observers to extract the statistical properties of stimuli (e.g., Chun & Jiang, 1998; Rosenthal, Fusi & Hochstein, 2001; Droll, Abbey & Eckstein, 2009; Fiser & Aslin, 2001, 2002) and is thought to occur implicitly (Saffran, Aslin & Newport, 1996; Fiser & Aslin, 2001; Turk-Brown, Jungé & Scholl, 2005). In a visual search tasks Geng and Behrmann (2002, 2005) for instance showed targets in ’high probability locations’ to be recognized faster than targets in ‘low probability locations’.
Either way, the modulation of attentional capture by onset distractors would speak against automatic bottom-up processing on the pre-attentive stage.
The stimulus material used in the present experiment was originally used by Godijn and Theeuwes (2002) who showed initial saccades to be strongly captured with it.

Method

Participants. Observers were 20 students of the Ecole Polytechnique Fédérale de Lausanne (EPFL) or the University of Lausanne. They were paid 20 CHF per hour. All observers were naïve as to the purpose of the study. All subjects had normal or corrected-to-normal visual acuity and accurate colour vision.
Apparatus, stimuli and task. Stimuli were presented on a PHILIPS 201B4 CRT monitor driven by a standard accelerated graphics card. The screen resolution of the CRT was set to 1024 by 768 pixels. The monitors white point was adjusted to be D65. Colour space was computationally linearised by applying individual gamma corrections to each colour channel (8 bits per channel). A Minolta CA-210 display colour analyzer was used for calibration measurements. Luminance measurements have been performed using a Minolta Luminance meter LS-100. Observers viewed the monitor from a distance

of 60 cm. An SMI eye tracker (iViewXTM HI-SPEED) with a sampling rate of 500 Hz (binocular tracking) and a tracking resolution of < 0.01° was used. The eye tracker was fitted with a chin and forehead rest to minimize head movements during the experiment.
The initial fixation display contained six red discs (CIE chromaticity coordinates: x=0.6289, y=0.3317; luminance: 4.2 cd/m²) presented equally spaced on an imaginary circle with a radius of 9.6° of visual angle around the centre of fixation. On the following search display, one of the red discs changed colour into an isoluminant grey (luminance: 4.2 cd/m²). The grey target disc appeared randomly at one out of four display locations, namely, the upper and lower, left and right locations. In a predefined proportion of trials, simultaneously to the target change (search display), a red onset distractor (OD) disc appeared in the display (CIE chromaticity coordinates: x=0.6289, y=0.3317; luminance: 14.0 cd/m², a pilot experiment showed that with a luminance of 14.0 cd/m² observers made saccades towards the onset distractor in only 50 % of the trials). The OD was presented on the same imaginary circle in between two disc locations but never next to the target. The OD was separated from the target by 30°, 90°, or 150°. Possible OD locations were randomly selected from “clock positions” 2, 4, 8, and 10 (not at 6 or 12). All discs had a diameter of 80 arcmin. See Figure 14 for a schematic illustration of the fixation and the search display.

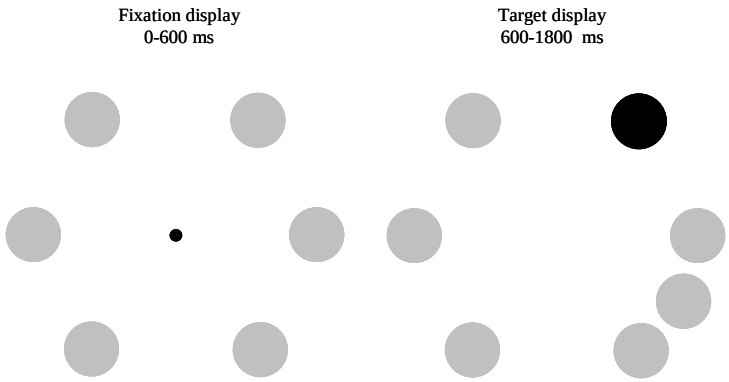


Figure 14: Illustration of the search displays (grey distractor discs were originally red; the black target disc was originally grey). After 600 ms fixation display, one of the red distractors turned to grey (right panel). In a certain proportion of trials, additionally a red onset distractor was presented simultaneously with the colour change. This onset distractor appeared in a position in between two of the discs (but never next to the target).

At the beginning of each trial, a white fixation point (diameter of 6 arcmin) was presented in the centre of the screen. After 300 ms, the discs appeared (fixation display). 600 ms after the disc onset, the colour of the target disc changed, a potential OD appeared (in case of an OD present trials) and the fixation dot disappeared simultaneously. The search display stayed visible for 1200 ms after target onset, with a subsequent inter-trial interval of 800 ms. If the latency of observers’ initial saccades

exceeded 250 ms relative to the target onset, acoustical feedback in the form of a low-pitch tone was given, indicating that observers initiated the saccade too slowly; if saccade latency was below 250 ms, a high-pitch tone feedback was given.

Design and Procedure. Observers' task was to fixate the fixation dot in order to initiate a trial and then to make a saccade to the target as fast and accurately as possible. They were informed about the presence of ODs, but were clearly instructed to ignore them. The display probability of OD trials was varied across blocks; participants were not informed about this. The percentage of OD trials within a block was either 0%, 20%, 50%, 80%, or 100%. Two experimental conditions were used. In the "run-up" condition, observers were first presented with blocks containing no ODs (0%), followed by 20%, and up to 100% ODs. In the "run-down" condition, OD trials were presented in the opposite order, that is, in the first block 100% ODs were presented, followed by 80%, down to 0%. While in the run-up condition the likelihood to ignore ODs was expected to be low at the beginning of the experiment (particularly in the 20% ODs condition immediately following the initial 0% ODs block), it was expected to be high in the run-down condition. Each block contained 100 trials. Observers completed two consecutive blocks of each of the five OD conditions. Within a block, OD trials and no-OD trials were randomly interleaved. Observers were randomly assigned to one of the two experimental conditions (run-up or run-down).

Data Analysis. Saccades with latencies (time elapsed between target onset and initiation of first saccade) faster then 80 ms or slower then 600 ms were discarded before data analysis. Saccades were defined as directed to one of the items (e.g., OD or target) if the initial fixation was inside a region extending +/- 7.5° of visual angle relative to one of the item locations. Trials were discarded from analysis when the fixation on the central point preceding presentation of the display items deviated by more than 1 arcdeg from the centre of this point. In the main analyses, only trials with ODs were considered. The 0% OD and 100% OD conditions (which have no or 100% OD trials) were not included in the main analyses, but used for a post-hoc analysis of saccade latencies.

Results

Saccade Destinations. Figure 15 shows the percentage of initial saccades to the OD as a function of the OD percentage. Initial saccades of the 20%, 50%, and 80% conditions were subjected to an ANOVA with the within-subject factor OD percentage (20%, 50%, and 80%) and the between-subject factor run-direction (run-up and run-down). The ANOVA revealed a significant main effect of OD percentage ($F(2,54) = 9.21$, $p < .001$). Neither the main effect of run-direction ($F(1,54) = .045$, $p = .83$) nor the interaction between the two factors ($F(2,54) = 1.71$, $p = .19$) was significant. The percentage of initial saccades towards the OD significantly decreased with an increase of OD percentage for both, the run-up and run-down condition. Pooling the data of the two conditions (run-up and run-down) revealed the attentional capture rate in the 20% OD condition as almost twice as high (67.0%) as in the 80% OD condition. In the 50% OD condition, attentional capture was higher

compared to the 80% OD condition and lower compared to the 20% OD condition. The 100% OD condition was not included in the main analysis because it was the first condition in the run-down group and used for familiarization and top-down expectancy set up (as the 0% condition in the run-down group). Even though this condition was mainly used to build up expectancies, the attentional capture rate was still lower compared to the 80% condition.

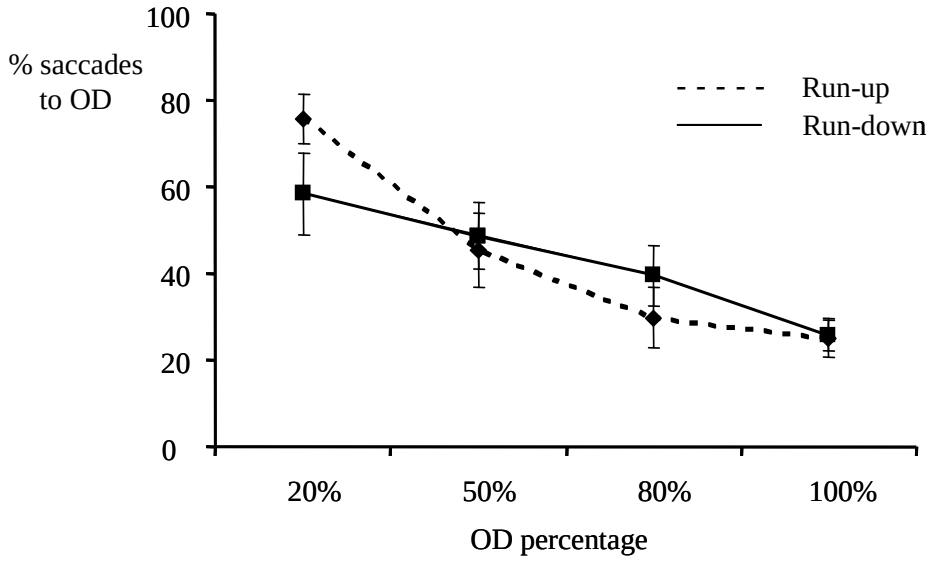


Figure 15: Percentage of initial saccades to the OD as a function of OD probability (20%, 50%, 80%, 100%) for the run-up and run-down conditions. In both conditions, more initial saccades landed on the OD when the OD display probability was low. Error bars indicate the standard error of the mean.

In summary, the capture probability was expected to increase with decreasing OD percentage for both, the run-up and the run-down condition. Practice increases over the course of the experiment and was expected to reduce the attentional capture rate, since in the run-down condition practise coincided with decreasing OD percentage the 'true' difference between both conditions on the level of the 20% OD probability might be underestimated. For the run-up condition practice coincided with increasing OD percentage, hence practice as well as OD percentage might have facilitated the task.

Inter-trial analysis. The main effect of OD percentage (the decrease of OD capture rate with higher OD percentage) could be due to inter-trial effects, in detail it might be that observers are able to suppress saccades to the OD in trials that are preceded by OD trials more efficiently compared to trials that are not preceded by OD trials. In the 80% condition, the majority of OD trials was preceded by OD trials, while in the 20% condition OD trials were only rarely preceded by OD trials. These inter-trial effects may reflect inhibition of the OD dimension carried over to the next trial. To investigate whether the main effect of OD percentage was due to such inter-trial effects, we conducted an inter-trial analysis. Because there was no significant interaction between the run-up and run-down

conditions in regard to the OD capture rate (Figure 16), the data of the two conditions in the inter-trial analysis was pooled. We compared the OD capture rate in trials that were preceded by OD trials (ODOD) with the capture rate in trials that were preceded by no-OD trials (nODOD). As shown in Figure 16, the capture rate did not depend on the presence or absence of an OD in the preceding trial. An ANOVA with the within-subject factors OD percentage (20%, 50%, 80%) and inter-trial transition (ODOD, nODOD) revealed a significant main effect of OD percentage ($F(2,112) = 11.25$, $p < .001$) but no effect of inter-trial transition ($F(1,112) = .153$, $p = .697$). (We performed the same analysis with the additional constraint that in preceding OD trials attention was not captured, and found no change of the pattern of results). Evidence for inter-trial effects would have been a lower OD capture rate in OD trials that were preceded by OD trials (that either captured attention or not) compared to preceding no-OD trials.

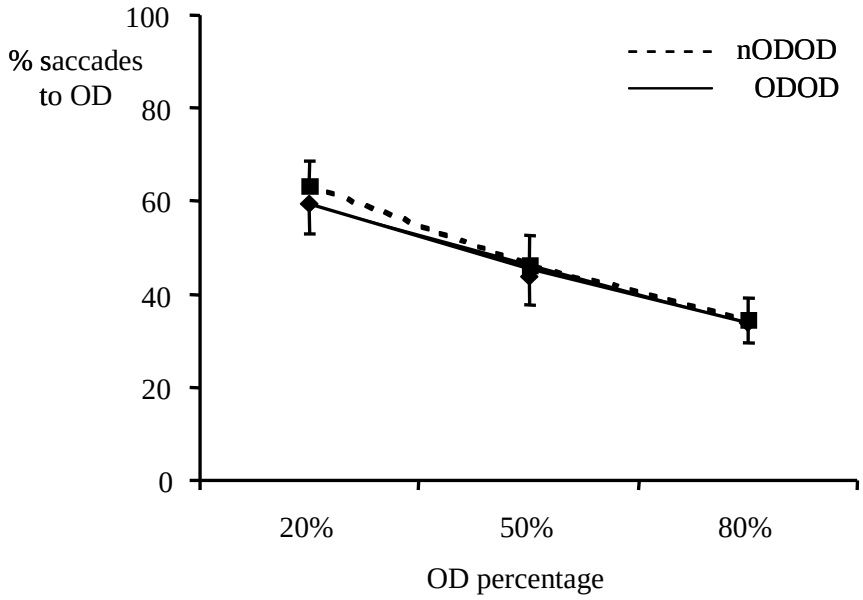


Figure 16: Inter-trial analysis. Percentage of saccades to the OD as a function of OD percentage (20%, 50%, 80%) for OD trials that were preceded by either a trial containing an OD (ODOD) or trials containing no OD (nODOD). No difference was found between the two conditions (ODOD and nODOD). Error bars indicate the standard error of the mean.

Saccade Latency. Figure 17 shows the latencies of the initial saccades as a function of OD percentage for the run-up and run-down condition. In the main analyses, only the 20%, 50%, and 80% conditions were considered. Latencies are shown separately for saccades to the target and to the OD, respectively. Latencies were subjected to a mixed ANOVA with the between-subject factor run-direction (run-up, run-down) and the within-subject factors OD percentage (20%, 50%, 80%) and saccade landing site (target, OD). We found a significant main effect of run-direction ($F(1,106) = 41.04$, $p < .001$) with shorter saccade latencies in the run-down (176.77 ms) compared to the run-up (201.20 ms) condition. Further, the main effect of saccade landing site was significant ($F(1,106) = 187.54$, $p < .001$) with

shorter latencies to the OD (162.88 ms) than to the target (215.09 ms). No significant main effect was found for OD percentage ($F(2,106) = 2.80$, $p = .07$). No interaction was significant.

In both the run-up and the run-down condition, saccades directed to the OD were faster than saccades to the target. The difference in saccade latencies might be explained by two (inter-dependent) effects. First, the high luminance increment of the ODs might have expedited the generation of a space-based saliency signal relative to the lower colour saliency of the target. Second, saccade latencies to the target might have been slower because of (costly) suppression of saccades to the OD in these trials. Interestingly, saccade latencies were not affected by the proportion of ODs presented within a particular block of trials (with the exception of somewhat higher latencies to targets in the run-up 20% ODs condition compared to the 50% and 80% ODs conditions). This suggests that saccade latencies were determined by processes that are not accessible by observers' long-term strategies, speaking in favour of a modulation of bottom-up effects.

To examine the somewhat unexpected difference found in saccade latencies of the run-up and run-down conditions, respectively, saccade latencies to targets in blocks with 0% and 100% OD were analyzed. While the 0% condition yielded a significant difference (204.77 ms and 179.91 ms for the run-up and the run-down condition, respectively; $t(18) = 2.899$, $p = .01$), the 100% OD condition did not (212.97 ms and 211.89 ms; $t(18) = 0.126$, $p = .90$). Moreover, in the 100% condition saccade latencies to the OD were also not significantly different (164.84 ms and 159.74 ms; $t(17) = .730$, $p = .48$). While these results might reflect an effect of the experimental manipulation, an interpretation in terms of different overall performance of observers in the two conditions is also possible (see Discussion).

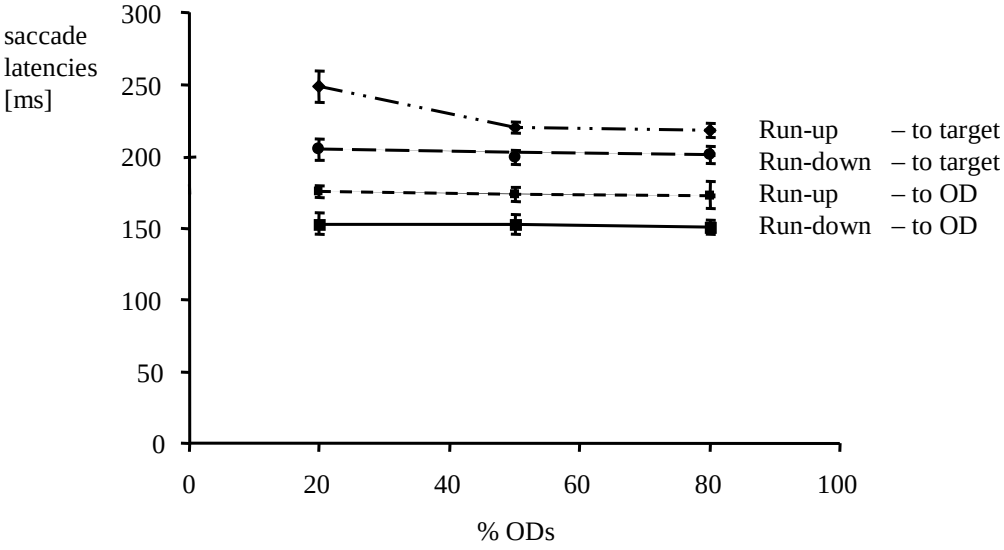


Figure 17: Initial saccade latencies to the target or to the OD as a function of OD percentage for the run-up and run-down conditions. For the 20%, 50%, and 80% conditions, latencies were shorter for saccades to ODs relative to the target for the run-up as well as the run-down condition. In the run-down compared to the run-up condition over all saccade latencies were shorter. There was no effect of OD percentage. Error bars indicate the standard error of the mean.

Discussion

It is generally accepted that two different attentional mechanisms operate in visual perception: top-down (or goal-driven) and bottom-up (or stimulus-driven) attention. Less agreement is found about the degree of automaticity or modulability of bottom-up attention. Only regarding the literature of attentional capture, some researchers argued for a purely automatic process (e.g. Belopolsky, Zwaan, Theeuwes & Kramer, 2007; Godijn & Theeuwes, 2002; Hickey, McDonald & Theeuwes, 2006; Theeuwes, de Vries & Godijn, 2003; Theeuwes, Kramer & Kingstone, 2004; Schreij, Owens & Theeuwes, 2008; Schreij, Theeuwes & Olivers, 2010; Theeuwes, 1991, 1992, 1994, 1996, 2004; Theeuwes, Atchley & Kramer, 2000; Theeuwes, Kramer & Belopolsky, 2004; Theeuwes & Van der Burg, 2008), others questioned that bottom-up attentional capture is automatic but instead can be modulated (e.g. Bacon & Egeth, 1994; Eimer & Kiss, 2008; Eimer, Kiss, Press & Sauter, in press; Folk & Remington, 1998; Folk, Remington & Johnston, 1992; Folk, Remington & Wright, 1994; Geyer, Müller & Krummenacher, 2008; Kiss, Jolicoeur, DellAcqua & Eimer, 2008; Leber & Egeth, 2006; Müller, Geyer, Zehetleitner & Krummenacher, 2009; Jonides & Yantis, 1988; Yantis & Egeth, 1999).

In Experiment 4, it was shown that attentional capture by high salient onset distractors (ODs), which are assumed to be the strongest cues to elicit bottom-up attention, was modulated by the display probability of the ODs. The findings suggest that bottom-up attentional capture is not purely automatic (for the relation of attentional and oculomotor capture see also Godijn & Theeuwes, 2002; Irwin, Colcombe, Kramer & Hahn, 2000; Ludwig & Gilchrist, 2002, 2003; Theeuwes, Kramer, Hahn, Irwin & Zelinsky, 1999; Wu & Remington, 2003).

Modulation is associated with the probability of distractor appearance. It can either be explained as modulation caused by the top-down goals of the participants (high incentive to suppress the distractor) or as modulation caused by implicit statistical learning. Attentional capture by the OD depended on the percentage of OD trials within a block: The higher the percentage of ODs, the smaller the proportion of saccades captured by the ODs. Müller et al. (2009) found the RT interference effect (increased mean RTs to OD relative to no OD trials) to be less marked for the group who started with the 0% condition compared to the group who started with the 100% condition. Geyer et al. (2008) however found the behavioural interference effect for observers in the run-up compared to the run-down condition to be increased in trials with 20% OD trials. In trials with 50% and 80% OD probability no marked differences between both groups was found. For the occulomotor data no group differences are reported. In the present data, though not significant, the initial saccades of the run-up group (75%) seemed to be more captured by the OD relative to the saccades of the run-down group (58%) in 20% OD trials. In 50% OD trials there was only very little difference between the groups (46% of the saccades of the run-up, and 50% of the saccades of the run-down group landed on the distractor) and in the 80% condition the difference was rather small as well but with a higher capture rate for the run-down condition (31% of the saccades of the run-up and 39% of the saccades of the

run-down group were captured by the OD). In general the interaction of the capture rates with the run-down and run-up group, respectively, in all three experiments with exactly the same manipulation is not very similar (this holds only true for the interaction over all, capture was manipulated in all three experiments). However, this variability of results speaks more in favour of a top-down hypothesis. First of all, processes dependent on observer's internal goals might underlie greater inter-personal variance compared to bottom-up learning effects which are expected to be more similar across individuals. The top-down hypothesis would assume, that in the run-down condition the incentive to suppress the OD would decrease with decreasing OD percentage, since an incentive to suppress the distractor is only given, if the cost of not suppressing the distractor is high overall. For the run-up group on the other hand the incentive to suppress the distractor is likely to rise for the 50% and 80% OD percentage blocks compared to their first block of 20% OD percentage, in which OD inhibition due to the sparse appearance of the OD and the lack of OD experience would be accepted as capturing attention. These two different top-down strategies if executed in extreme would equalise the capture rates of the two groups (as found in the present experiment and more or less also in Geyer et al.'s (2008) data). Under the assumption of great inter-individual variance with respect to the internal goals and intentions the top-down hypothesis could also account for the diverse capture rates between the three experiments.
On the other hand, the statistical learning hypothesis would assume an interaction between the groups, since practice effects and decreasing capture probability (due to increasing OD percentage) go hand in hand in the run-up condition, but not in the run-down condition. The capture rate in the run-up condition should increase with increasing OD probability (steep curve of capture rate), but the capture rate of the run-down condition should be low over all blocks, independent of OD probability decrease (shallow curve of the capture rate, as found by Müller et al., 2009). Since both capture rate patterns were obtained in three experiments using the same design, the effect of modulated attentional capture might be caused by both mechanisms, statistical learning and top-down control. In any case, inter-trial modulation was proved not to account for the results. If inter-trial transitions in which an OD trial is preceded by another OD trial were higher in blocks with high OD percentage compared to low OD percentage. This higher OD-OD trials frequency might have caused the OD percentage effect (the lower capture rate with higher OD percentage), for example, because of automatic inter-trial priming (e.g.; Maljkovic & Nakayama, 1994, 1996; Walthew & Gilchrist, 2006). However, no such effect was observed. The OD capture rate in OD trials preceded by OD trials was not higher than in trials that were preceded by trials without an OD.

The examination of saccade latencies showed that latencies to the targets were always longer than to the ODs. This supports the assumption that a strong bottom-up signal was generated by the OD. There was no main effect of OD percentage. Overall, latencies in the run-up condition were higher compared to the run-down condition. A similar difference was found in the 0% condition (no OD trials) but not

in the 100% condition. It is to speculate whether this difference, found in all conditions except the 100% condition, reflects effects of the experimental manipulation or is inherent to initial group differences. It could be argued that longer latencies in the run-up compared to the run-down group were due to the different learning histories during the first blocks. While observers in the run-down condition learn early during the course of the experiment to suppress saccades to the OD, observers in the run-up condition do not (as observers in the latter group start with 0% distractors which does not require suppression). The shorter latencies to the target in the run-down condition compared to the run-up condition could therefore reflect a maintained effective suppression of saccades to the OD. However, it is unclear why this effect was only observed in terms of saccade latencies but not in the rate of attentional capture where no differences between the two conditions were found. However, maintained suppression could not explain why also latencies to the ODs are shorter in the run-down compared to the run-up condition. One potential source for shorter saccade latencies in the run-down group, namely express saccades (i.e. saccades with very short latencies, Fischer & Ramsperger, 1984), was excluded by investigating individual saccade latencies (shortest average latency to the target was 167ms).

To conclude, in Experiment 4 it was shown that modulation of attentional capture is possible when distractors are onset stimuli that strongly capture attention. However, the present results also showed, that even with practice or high motivation, observers in both groups were not able to completely overcome attentional capture by onset distractors. But clearly, be it by bottom-up statistical learning or top-down controll, the capture effect of salient onset distractors was modulated in the present experiment.

6. Development of mechanisms underlying visual search; categorical and cognitive aspects

Since the ability to select relevant information for the control of current thinking and behaviour is one of the core cognitive abilities in humans the question must be raised, whether this ability is innate and if not, when it is evolved in children's development. Over the last few decades some amount of research has focused on the development of selection mechanisms in children by means of visual search tasks (note, that visual search paradigm was adapted with respect to particular age groups, see below). The basic question always was, whether infantile and adult information selection processes in visual search are comparable. For a long time, researchers explained the processes underlying selection of visual information in infants and children as the same as for adults. This knowledge has been gained by studies including observers of several ages; from the early infancy of 3 to 6 months of age (Adler & Orprecio, 2006; Bertin & Bhatt, 2001b; Colombo, Ryther, Frick & Gifford, 1995; Rovee-Collier, Hankins & Bhatt, 1992; Rovee-Collier, Bhatt & Chazin, 1996) up to children between 1 and 9 years of age (Gerhardstein, Kraebel, Gillis & Lassiter, 2001; Gerhardstein & Rovee-Collier, 2002). However, this holds especially true for the feature search, where consistently parallel and efficient processing of the stimuli was observed (Bertin & Bhatt, 2001b; Colombo et al., 1995; Gerhardstein et al., 2001; Gerhardstein et al., 2002; Rovee-Collier et al., 1992; Rovee-Collier et al., 1996), whereas in conjunction search tasks more inconsistent results were revealed. Compared to the simultaneous search (flat RT search functions) for feature targets, Gerhardstein et al. (2002) found RTs to increase with increasing set size, indicating a serial, inefficient search, comparable to adult observers. Their youngest age group, the 12 month olds, were unable to conduct the feature-conjunction search. But nevertheless these results were taken as evidence for a qualitatively equal visual search performance in children aged 18, 24 and 36 months and adults. In their experiments, Bertin and Bhatt (2001b), too, found 5 month olds to be able to detect a feature target, but completely failed to detect a conjunction target. They conclude that, as in adults, the search for a unique singleton feature target differs qualitatively from the search for a unique conjunction target, regardless of the fact, that adults were able to detect a conjunction target, whereas infants were not. Despite these results, explained as similar search performance of children and adults, a potential developmental progression was accepted with respect to serial search mechanisms by Gerhardstein et al. (2001, Exp. 1). In a very precise experiment they also observed search functions for a serial type of search (search for a T among Ls) compared to a parallel search (search for a + among Ls) to be more steep for two-, three-, four- to six-, seven- to nine- and 20-year olds (see also Trick and Enns (1998) for similar findings on six-, eight-, ten-, 22- and 72-year old observers). But they clearly stated that the RTs in children increased with increasing set size in a much greater amount compared to the RTs of the 20 year old adults. Gerhardstein et al. (2001) even strengthened this finding with reports of the observed behaviour of the participants. The younger children up to the age of 6 seem to implement the serial

search even manually, by serially hunting through the presented items with their fingers on the display in order to detect the target. The older children clearly didn't search for the target that overtly, but still their data too was differentiable from the one of the adults.

However, Adler and Orprecio (2006) pointed to a crucial point, concerning the comparability of most of the above mentioned studies on children with studies on adults, which cannot be by-passed. To deal with the lack of a perfectly developed ability to conduct manual responses and to understand verbal instructions, especially in infants, other methods than RT recording measurements were used. Search and detection behaviour in infants is typically measured with methods including their looking, like in novelty preference procedures, where a single novel or familiar feature surrounded by distractors has to be detected in a display (Bertin & Bhatt, 2001b; Colombo et al., 1995). The preferential looking to a certain location in the display is then manually recorded by the examiner. In other designs, paradigms recording gross motor skills are used, like in the mobile-conjugate reinforcement procedure (Rovee-Collier et al., 1992; Rovee-Collier, 1996). In this operant measurement of recognition, infants are presented with a (3D) mobile consisting a target and distractors. Recognition of the target is measured in varieties of the kick rate to the according mobile. None of these paradigms provides measures that are comparable with the RTs obtained in visual search tasks that are recorded in milliseconds.
However, there were also experiments recording RTs, by means of key presses on a keyboard (Trick and Enns, 1998) or direct pointing to the target on a touch screen (Gerhardstein et al., 2001, 2002).
As already reported above, in these studies, flat search functions were revealed, independent of the age of the participants, which is in line, however, with findings from preferential looking or kick rates paradigms. But in contrast to these studies, RT studies with children were able to report significant effects of age: the younger were the observers, the slower were RTs.
Unfortunately statistically significant differences in the RT data between the several ages were never reported. Nevertheless, this acceleration of RTs over the observer's ages clearly shows developmental effects.
Gerhardstein et al. (2001, 2002), based on Anderson, Nettlebeck, and Barlow (1997) and Bard, Hay, and Fleury (1990), explained the decline of the RTs with ongoing motor maturation speeding up RTs in older children and adults compared to young children. Trick and Enns (1998) stated as well, that differences in mean RTs are due to differences in motor speed alone.

Adler and Orprecio (2006) recorded eye movements, as a method that is also based on looking (as the preferential looking paradigm), but by recording saccade latencies (measured in milliseconds) instead of rough saccade directions and possible endpoints (preferential looking paradigm). The occulomotor system is known as being highly linked to the attentional system and therefore an ideal measurement for attentional processes (see also Experiment 4 of this thesis), especially in pre- verbal infants. In their study, Adler and Orprecio (2006) collected eye movement latencies of three-month olds infants

and adults in a feature search (search for a + among Ls) with varying set sizes. For infants and adults flat search functions in terms of saccade latencies were obtained in target-present arrays. In target-absent arrays (note, that this study was the first that assessed target absent trials and compared them to target present trials), saccade latencies significantly increased with increasing set size for both, infants and adults. Adler and Orprecio (2006) concluded that "this would seem to suggest, that infants' attentive processing, search mechanisms and target selection for saccades are similar to adults'" (p. 200). On the other hand, there was a main effect of age regarding saccadic latencies, which is equivalent to the accelerated, age related, over all RTs found in the studies of Gerhardstein (2001, 2002). Adler and Orprecio as well, explain this by maturation of the speed to initiate a saccade, by completing myelination of sensory and motor pathways. Attentional mechanisms are not thought to be involved in the maturation process, because the relative slopes of the search functions in infants and adults were nearly the same (5.2 vs. 7.2 ms/item in target present, 23.9 vs. 25.7 ms/item in target absent displays) only the y-intercepts of the functions differed significantly. Unfortunately the exact y-intercepts are not mentioned in the paper, but as can be read out of the graphs for children y-intercepts are increased approximately 110 ms for target present trials (380 vs. 270 ms) and approximately 90 ms for target absent trials (430 vs. 340 ms).

However, until now, only one study was conducted, which results were not interpreted as reflecting similar search mechanisms in infants, children and adults. In a series of RT experiments Donnelly, Cave, Greenway, Hadwin, Stevenson and Sonuga-Barke (2007) tested six- to seven- and nine- to ten-year old children and adults and found several effects that were related to the age of the observers. In a conjunction search task (Experiment 1), search was serial and effortful in all age groups, target absent trials were responded to slower than target present trials and the search rate per item was inversely related to age; the younger the observers, the higher the search rate. Search slopes for target present and absent responses, respectively, were 102 and 204 ms/item for the 6/7 year olds (±100 ms), 37 and 59 ms/item for the 9/10 year olds (±22 ms) and 30 and 31 ms/item for the adult observers (±1 ms). Target absent trials were responded to slower than target present trials in all age groups, but the ratio (slope differences) between these two conditions decreased with increasing age.
In the feature search (Experiment 1) there was no effect of set size for any age group. Again RTs for target absent trials were increased compared to RTs for target present trials in all age groups, and again, the ratio (mean absent minus mean present RTs per age group) decreased with increasing age. For both tasks, mean RTs for the children were slower than for adults. Donnelly et al. (2007) concluded that in feature, as well as in conjunction search, evidence for a developmental component was found.

Taken together, most of the studies investigating visual search and selective attention in infants and children are not comparable to the studies on adults, because of different methodology and measurements. Some studies, which are comparable, measuring RTs or saccade latencies for example, were interpreted in such a way that processes underlying search, seem to be similar between children and adults, and that the only development-related finding, the overall decrease of processing speed is caused by ongoing motor maturation. However, the results of Donnelly et al (2007), say the more pronounced results of the feature conjunction compared to the simple feature search (absent-present ratio) seem to be a first piece of evidence that other (cognitive) factors, than just simple motor maturation might be involved in the development of search speed. A related result was also found by Gerhardstein et al. (2001) who showed set size effects on RTs to be more dramatically in children than adults.

In the following two experiments the development of the categorisation effects (Experiment 5; simple feature search) on the one and of cognitive search components (Experiment 6; feature conjunction search) on the other hand will be investigated in order to contribute to the debate about whether mechanisms underlying visual search of children and adults are the same or not.

Experiment 5: Development of categorical effects in simple feature search

Purpose of the present study

The ability to subsume single features to categories enables fast processing of visual input, because building categories reduces the complexity of visual information. The cognitive system has to generalize across physically different properties of objects, whereas the grade of generalization varies with levels of category abstraction (Palmeri & Gauthier, 2004). The ability of adult observers to pre-attentively unite different concrete features present in the field to superordinated constructs (i.e. to create feature categories/dimensions) is measurable in terms of RTs. The requirements of feature-based processing leads to RT-costs, compared to dimension-based processing (e.g. see slowed RTs for discrimination versus simple detection tasks in Cohen and Magen (1999), Found and Müller (1996) and Gramann et al. (2007) or Experiment 1 and 2 of this PhD).

However, this ability to categorise basic visual features was not found to be present in children observers. Gerhardstein, Renner, and Rovee-Collier (1999) tested whether the detection of a colour pop-out target was affected by categorical and/or perceptual target-distractor similarity in three-month old infants (Experiment 2). Children were presented with a mobile composed of seven discs on which the stimuli (+) in different Munsell colours were attached. The mobile was constructed as a pop out arrangement, with a target item in a novel and six distractor items in a familiarised colour, which was trained before the test phase by conjugate reinforcement (see Rovee & Rovee, 1969). Four

experimental conditions were tested: the novel target colour was either from the same or a different colour category than the colour of the familiarised items (red vs. orange) and the novel target was either perceptually similar (two steps on the Munsell scale away) or dissimilar (three steps on the Munsell scale away) to the non-target colours. Baseline kick rates towards the familiarised mobile were compared to kick rates towards the pop-out mobile, revealing a reduced kick rate ratio for perceptually dissimilar compared to similar colours. Note that with this method, in contrast to the typical novelty preference tests within the framework of preferential looking, a decrement of activity (kick rate) indicates here the detection of a novel array. This was taken as evidence, that performance was controlled by the novel target and therefore the novel target must have differed from the familiar items. No such effect was found for the condition in which the colour category had differed between target and non-target items. The authors concluded that categorical dissimilarity did not affect colour pop-out (see Davies and Franklin (2002) for a detailed critique on that experiment).

These results perfectly fit the Bruner, Olver and Greenfield's (1966) assumption, that younger, compared to older children categorise perceptually (perceptual dissimilarity affected colour pop-out) rather than conceptually (categorical dissimilarity did not affect colour pop-out). Donnelly et al. (2007) found comparable results supporting this general assumption. In their feature singleton search task (Experiment 1 and 2) for colour (purple, red), orientation (oblique, vertical) and size (small, large) singletons, they found, that the younger children aged six and seven were significantly faster in detecting colour compared to orientation targets. This was not the case for the older children and adult participants. In a third experiment, using a discrimination task with only two items presented in the display (participants had to make same-different judgements) they wanted to investigate, whether there was a general superior discrimination for colour over orientation, in other words, whether colour features were easier to categorise for younger children than orientation features. They found no significant difference in RTs for colour versus orientation, concluding that: "differences found between detection of colour and orientation targets in Experiment 1 and 2 were related to search and not to discrimination" (Donnelly et al., 2007, p. 132) and that therefore, it is "possible that six- to seven-year olds might only be able to search within a particular stimulus dimension at any given time" (Donnelly et al., 2007, p. 134). This conclusion is totally in line with Frith and Frith (1978) who postulated that: "At an early age (2 to 5 years), the child already shows evidence of categorization, but sorts without plan and may constantly shift his criterion for sorting. At a more advanced stage (5 to 8 years), the child achieves genuine classification, but usually still only attends to one dimension of similarity at a time. At a later stage (after age 8), the child learns to master true multiplicative classification and can attend to several dimensions of similarity at once" (Frith & Frith, 1978, p. 414). Further support for this categorisation hypothesis came from Tversky (1985) who claimed that at the age of schooling (the age of six, in Switzerland) a significant cognitive change toward the organisation in concepts is happening. Ross, Gelman and Rosengren (2005) indeed found children aged 5 years and eleven month to be able to accurately categorise figures according to their colours in 77.3% of the

cases, whereas children aged six years and seven month already answered correctly in 97.1% of the trials.

Overview of Experiment 5

In Experiment 5 the development of categorisation abilities was investigated by means of inter-trial analyses in a feature target search. The aim was to replicate earlier results of categorical search effects in observers aged eight years and above, whereas it was expected to find distinct, concrete feature-based search effects in observers younger than eight (Donnelly et al., 2007; Frith & Frith, 1978; Ross et al., 2005; Tversky, 1985). Additionally over all search RT differences between the younger and the older children on the one hand and the older children and adults on the other hand should be modulated by age, as found in earlier experiments measuring RTs (Burack, Enns, Iarocci & Randolph, 2000; Donnellly et al., 2007; Trick & Enns, 1998) and saccade latencies (Adler & Orprecio, 2006; Yang, Bucci & Kapoula, 2002). Until now, the whole age span between younger children and young adults was never tested. This was done in Experiment 5 in order to be able to differentiate further RT- and error-based developmental steps. Therefore, not only six- and eight-year olds (the critical ages), but the whole age range up to the young adult age (ten-, twelve-, 14-, 16-, 18- and 20-year olds) was investigated. Slowed RTs in children were commonly explained in terms of sustained motor maturation by ongoing myelination of sensory and motor pathways (Adler & Orprecio, 2006; Trick & Enns, 1998, Yang et al., 2002). In other words, with increasing age, children get faster in visual search due to faster sensory detection of the signal and faster motor response executions; two process components which are reflected in simple detection tasks. In order to control for the sensory-motor contingent in the development of visual search RTs in the present experiment a simple RT task was conducted additionally to the choice RT visual search task.

Method

Participants. Participants were 129 children and young adults aged between six and 20 years of age. According to their age, observers were divided in eight age groups: the six-year olds (N = 21, 9 female), the eight- year olds (N = 17, 9 female), the ten-year olds (N = 17, 10 female), the twelve-year olds (N = 17, 15 female), the 14-year olds (N = 17, 10 female), the 16-year olds (N = 14, 8 female), the 18-year olds (N = 12, 5 female) and the 20-year olds (N = 14, 7 female). All participants had normal or corrected-to-normal vision, all reported normal colour vision. All observers were naïve as to the purpose of the experiment and none of them had previous experience in visual search tasks. All participants were pupils in Zurich acquired through the institute of developmental psychology of the University of Zurich. All observers were tested by student assistants, who received CHF 30.- per hour. After completion of the test, children received lunch.

Apparatus, stimuli and task. All children were tested individually in a separate room of their schoolhouses. The rooms were slightly dimmed in order to create standardized lighting conditions.

Participants were seated with the back to the wall to prevent light reflections on the display. The experiment was conducted on Acer TravelMate 4672LMi laptops (Intel Core Duo T2300, 1.66 GHz, 1024 megabytes of RAM), running under the Windows XP operating system and using the "Cogent 2000" toolbox (www.vislab.ucl.ac.uk/Cogent/) for MATLAB (Mathworks, Inc.). Stimuli were presented on 15 inch TFT LCD laptop displays at a screen resolution of 1280 × 1024 pixels, put in an upright position (frame rate 60 Hz). Responses were recorded with the laptop key pad with the irrelevant keys covered by a custom-made felt cover. Only the three relevant keys (right- and left-hand control key and the space bar) were visible and responsive. Additionally, the control keys were covered with a red (left) and green (right), respectively, coloured tape to make them more distinctive for the children. Observers viewed the display from a distance of approximately 65 cm.

The experimental display consisted of 49 items (bars) which were arranged in a matrix of 7 × 7 rows and columns. The green vertical distractors and the targets were all isoluminant (4.5 cd/cm²) and displayed against a dark grey background (0.7 cd/ cm²). Each target differed from the non-targets in either the colour (red or blue) or the orientation (45° right- or left-tilted) dimension. All search items subtended 0.2° × 1° of visual angle and their positions were randomly jittered by maximally 0.5° of visual angle relative to the centre of the virtual matrix cells, in order to prevented observers from perceiving the display in the form of collinear rows and columns. The spacing between the centres of the items without jitter was 1.9° of visual angle on the x- and the y-axis. The matrix display was drawn in the central area of the display and, including the jitter, subtended a maximum of 13.3° of visual angle in width and 18.4° of visual angle in height. Note that this information is approximate; participants were not restrained from moving and some, especially younger children, did so. Targets were presented at one randomly selected location within the inner 5 × 5 matrix to maintain local feature contrast effects (and to avoid 'edge effects' in terms of slower detection of targets presented at the edges of a display). Observers were not informed of this.

Procedure. Target-absent and -present trials were presented randomly. 60% of the experimental trials were target present, 40% target absent trials. The four target types were equally likely to appear in present trials: 50% of the presented targets were defined in the colour dimension (50% in red, 50% in blue), 50% in the orientation dimension (50% right-tilted, 50% left-tilted). Participants were able to get familiar with the task by performing twenty exercise trials. Following familiarization, the observers, according to their age groups, completed between three and six experimental blocks, each consisting of 96 trials. The six-year olds completed three blocks (288 experimental trials), the eight- and ten-year olds four blocks (384 experimental trials), the twelve-year olds five blocks (480 experimental trials) and the 14-, 16-, 18- and 20-year olds completed six blocks (576 experimental trials). The blocks were additionally divided in three sub blocks to give observers the chance to take brakes properly in order to avoid fatigue effects. Note that for all age groups, independent of number of blocks the experiment lasted about 30 minutes. In case the experiment exaggerated the 30 minutes

border it was aborted. At the start of each trial, a white fixation cross was presented for 700 ms in the centre of the display followed by a blank of 200 ms. The experimental display appeared and remained visible until response. The target-present response was given with the right control key (green cover), the target absent response with the left control key (red cover) of the keyboard. At the end of every block observers received feedback about their accuracy and reaction times (RTs) – participants older than eight by the monitor, participants aged six and eight verbally by the investigator. Generally every participant was lauded for his performance and motivated to do even better. Participants aged six and eight were instructed by the investigator and were told a cover story, instructions for the older observers were displayed on the computer screen. All observers were instructed to respond as quickly and accurately as possible. After the visual search task, all participants completed one additional block (of 64 trials) of a simple RT task. Observers were instructed to press the space bar as soon as they detected the onset of a search array on the display. Stimuli were exactly the same as in the search task, but observers did not discriminate target presence and absence.

Results

Five participants (one aged six, three aged eight, one aged 14) were excluded from analysis due to exceedingly high standard deviations (examined by visual exploration) in their RT data. 3.0% of all trials in the detection task and 1.5% of all trials in the search task were excluded from analysis for being either responded to too slow or too fast (anticipatory answers). RTs with more than three standard deviations from the mean were calculated for each age group separately and excluded from analysis (2.0% of the data in detection task, 1.5% of the data in the visual search task). Furthermore four participants were not able to complete the detection task (one aged eight, one aged twelve, one aged 16 years and one aged 20). For the data analysis univariate analyses of variance (UNIANOVAs) and for multiple comparisons of the conditions Bonferroni corrections were used.

Errors. Over all, error rates in the search task were very low; for the six-, eight-, ten-, twelve-, 14-, 16-, 18- and 20- year olds error rates were 4.8%, 2.0%, 3.5%, 3.2%, 3.3%, 2.0%, 1.9%, 2.1%, respectively . An UNIANOVA with the factors error (within) and age (between; 6, 8, 10, 12, 14, 16, 18, 20) revealed a significant main effect of age [$F(7,116) = 3.975$, $p = .001$]. Repeated contrasts, by comparing every age group with the corresponding next older one, showed only the differences in the error rates between the six and the eight year olds and the eight and the ten year olds to be significant. The eight year olds made less errors than the six [$p < .001$] and the ten [$p = .047$] year olds. None of the other comparisons reached a significant level [$F(7,116) = 3.975$, all *n.s.*].
In a detailed error analysis errors in present trials that were responded to as target absent trials (miss) and absent trials that were responded to as target present trials (false alarm) were analysed in an repeated measures ANOVA with the within factor error type (miss, false alarm). Age (6, 8, 10, 12, 14, 16, 18, 20) was the between factor. There was no significant main effect of error type [$F(1,116) =$

1.211, *n.s.*], but the interaction of error type x age reached statistical significance [$F(7,116) = 2.715$, $p = .012$]. Eight independent t-tests revealed that the three oldest age groups, the 16-, 18- and 20-year olds, made more misses than false alarms (2.3% vs. 1.7%; 2.0% vs. 1.7%; 2.4% vs. 1.5%). However, the effect was only significant for the 20-year olds [$t(13) = 2.397$, two-tailed $p = .032$] and not for the 16- [$t(13) = 1.380$, *n.s.*] and 18-year olds [$t(11) = 1.002$, *n.s.*]. Interestingly the effect was exactly reversed in the younger age groups aged six, eight, ten and twelve. Here more false alarms than misses were made (5.3% vs. 4.5%; 2.7% vs. 1.5%; 3.9% vs. 3.3%; 3.5% vs. 2.9%), though the effect was only significant for the eight-year olds [$t(13) = 3.394$, two-tailed $p = .005$] and not for the six-year olds [$t(19) = 1.273$, *n.s.*], the ten-year olds [$t(16) = 1.686$, *n.s.*] and the twelve-year olds [$t(16) = 1.309$, *n.s.*]. The 14-year olds made an equal number of misses and false alarms (3.3% vs. 3.3%).

Reaction times. The RTs of the search task for target absent and present trials were analysed in a repeated measures ANOVA with the within factor trial (absent, present) and the between factor age (6, 8, 10, 12, 14, 16, 18, 20). The main effect of trial [$F(1,116) = 63.262$, $p < .001$], as well as the interaction of trial x age [$F(7,116) = 2.564$, $p = .017$] was revealed to be significant. All in all, participants were faster in target present trials (599.3 ms) compared to target absent trials (671.8 ms). This RT pattern of increased RTs in target absent compared to present trials was significant in all age groups (Table 6a), as revealed by eight independent t-tests [six-year olds: $t(19) = 3.237$, two-tailed $p = .004$; eight-year olds: $t(13) = 5.344$, two-tailed $p < .001$; ten-year olds: $t(16) = 3.094$, two-tailed $p = .007$; twelve-year olds: $t(16) = 6.020$, two-tailed $p < .001$; 14-years olds: $t(15) = 3.549$, two-tailed $p = .003$; 16-year olds: $t(13) = 4.269$, two-tailed $p = .001$; 18-yar olds: $t(11) = 4.460$, two-tailed $p = .001$; 20-year olds: $t(13) = 2.785$, two-tailed $p = .015$]. Replicating Donnelly et al. (2007) the ratio between target absent and present RTs (calculated by subtracting the present from the absent RTs) decreased with increasing age (133.0 ms, 120.8 ms, 101.9 ms, 60.6 ms, 57.4 ms, 44.5 ms, 30.6 ms and 31.2 ms for all age groups in ascending order). However, repeated contrasts showed the differences in the absent-present ratio not to differ significantly between successive age groups [$F(7,116) = 2.564$, all *n.s.*].

In further analyses, target absent and present RTs were treated separately. Target present RTs of the search task were analysed in a separate repeated measures ANOVA with the factors dimension (colour, orientation) and age (between; 6, 8, 10, 12, 14, 16, 18, 20). The main effect of dimension was significant [$F(1,116) = 111.966$, $p < .001$] due to overall faster processing of colour signals (581.7 ms) compared to orientation signals (616.8 ms). However, the interaction was not significant [$F(7,116) = 1.288$, *n.s.*], the dimension of the target did not affect the over all RT distribution over the age groups. In order to compare RTs of the search (only present RTs were included) and the simple RT task (always a present signal), a repeated measures ANOVA with the factors task (search, detection) and age (between, 6, 8, 10, 12, 14, 16, 18, 20) was conducted. The main effect of task [$F(1,112) = 1800.488$, $p < .001$], as well as the interaction [$F(7,112) = 17.348$, $p < .001$] reached significance.

Eight additional t-tests confirmed that the detection task (Table 6b) was responded to significantly faster than the present trials of the search task in all age groups [six-year olds: $t(19) = 16.464$; eight-year olds: $t(12) = 18.162$; ten-year olds: $t(16) = 13.615$; twelve-year olds: $t(15) = 28.180$; 14-year olds: $t(15) = 18.029$; 16-year olds: $t(12) = 16.976$; 18-year olds: $t(11) = 18.261$; 20-year olds: $t(12) = 27.787$, all two-tailed ps $< .001$].

Apparently for both trial types of the search task (absent and present) as well as for the simple RT task mean RTs decreased with increasing age in a decelerated fashion, two UNIANOVAs with the between factor age (6, 8, 10, 12, 14, 16, 18, 20) confirmed this impression [target present: $F(7,116) = 43.310$, $p < .001$; target absent: $F(7,116) = 28.454$, $p < .001$]. Significant RT differences between the age groups were evaluated by means of repeated contrasts: the six-year olds were significantly slower than the eight-year olds [$p < .001$], the eight-year olds were significantly slower than the ten-year olds [$p = .013$], the ten-year olds were significantly slower than the twelve-year olds [$p = .001$] and the 14-year old were significantly slower than the 16-year olds [$p = .016$] in the target present search. All other RT differences between the according age groups were not significant (between the twelve- and the 14-year olds, the 16- and the 18-year olds and the 18-and the 20-year olds [$F(7,116) = 43.310$, *n.s.*]). Nearly the same RT distribution was found for target absent search trials: RTs differed between the six- and the eight- [$p = .002$], the eight- and the ten- [$p = .049$] and the ten- and the twelve-year olds [$p = .003$]. The contrast between the 14- and the 16-year olds was not significant, though there is tendency [$p = .070$]. All other comparisons between subsequent age groups were not significant [$F(7,116) = 28.454$, *n.s.*].

According to Donders (1868, 1969) RTs of forced choice reaction tasks are composed of four distinct and separable processes: first the signal detection, second the signal discrimination, third the response selection and fourth the response execution, whereas, in simple RTs only the signal detection and the response execution stage are reflected. Since in RTs the processing components comply with the condition of pure insertion, the simple RTs can easily be subtracted from search RTs, resulting in a RT distribution associated with the cognitive search processes of signal discrimination and response selection. With this procedure the time associated with search components (signal discrimination and response selection) are factored out and can be analysed regarding to its developmental progress over the age groups. Therefore, in order to dissociate between motor and cognitive contingents of the target present search acceleration repeated contrasts were conducted for the simple RTs and the RTs associated with cognitive mechanisms (difference RTs of the simple and the target present choice RTs Table 6c). An UNIANOVA revealed a significant effect of age (6, 8, 10, 12, 14, 16, 18, 20) on simple RTs [$F(7,112) = 28.961$, $p < .001$] and repeated contrasts showed RTs to differ substantially between the three youngest age groups, the six- and the eight- [$p < .001$] and the eight- and the ten-year olds [$p = .001$] only. Therefore motor maturation can only explain (at least part of) the decrease of the search RTs between the six- and the ten-year olds. After the age of ten, it seems that RTs are no longer accelerated by further motor maturation. For the cognitive search RTs as well an UNIANOVA was

conducted [$F(7,112) = 17.352$, $p < .001$] and here significant differences between participants aged 10 and 12 [$p = .001$] and 14 and 16 [$p = .016$] were obtained. Exactly between these age groups, the variance in the search RTs can't be explained by the sensory-motor RTs of the simple RT task. See also Figure 18 for an illustration of all target present RTs (search, simple and cognitive RTs) inclusive substantial RT differences across age groups.

Age	6	8	10	12	14	16	18	20
a) Search RTs								
Target present	878.7	744.6	652.3	533.6	551.8	467.5	489.2	471.6
Target absent	1011.7	856.0	754.2	605.8	609.1	514.2	519.8	503.3
b) Simple RTs	406.6	324.5	264.5	247.4	239.5	231.6	234.1	215.6
c) Cognitive RTs	472.1	420.0	387.9	286.2	312.3	235.9	255.1	255.9

Table 6: Mean RTs (in milliseconds) of all eight age groups for target present and absent trials of the feature search task (a) and the simple RT task (b). Mean RTs associated with cognitive factors (c) were revealed by subtracting b from a (present trials).

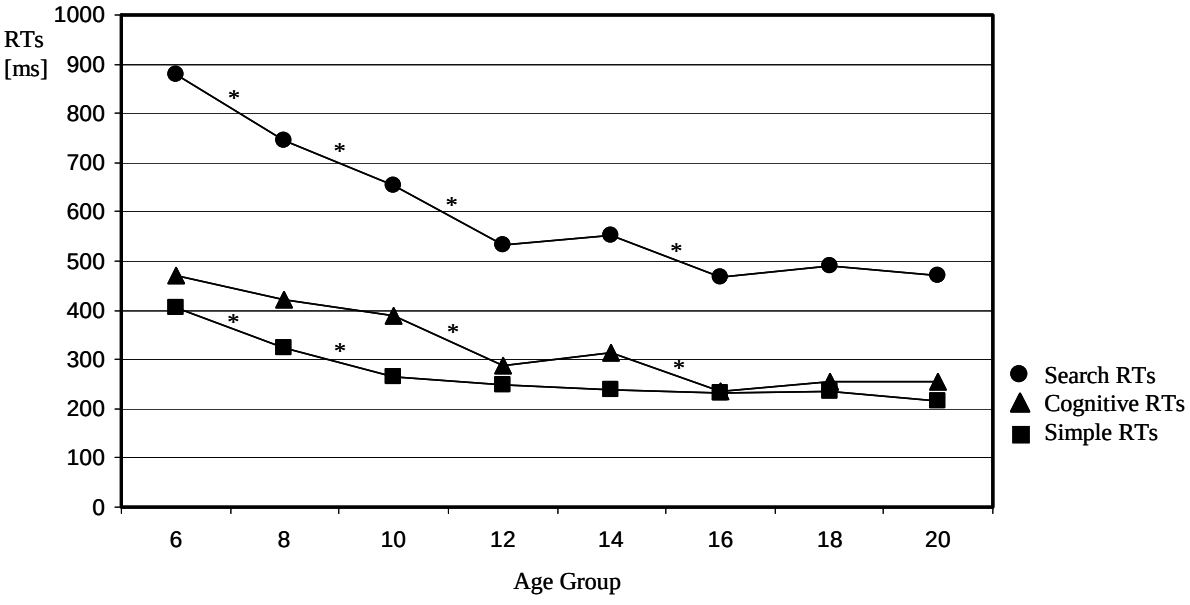


Figure 18: Mean search, simple and cognitive RTs (in milliseconds) of all eight age groups for target present trials only. Mean RTs associated with cognitive factors were revealed by subtracting simple from search RTs. Stars (*) indicate significant RT differences between the according age groups.

Inter-trial effects. For the inter-trial analysis three types of inter-trial transitions were of interest: sDsF (same dimension same feature), sDdF (same dimension different feature) and dD (different dimension) transitions (Table 7). Feature- and dimension-based previous trial effects were analysed separately for each age group in repeated measures ANOVAs with the factors inter-trial transition (sDsF, sDdF, dD) and dimension (colour, orientation). The main effect of inter-trial transition was significant for each age group [six-year olds: $F(2,38) = 11.756$; eight-year olds: $F(2,26) = 11.008$; ten-year olds: $F(2,32) = 13.237$; twelve-year olds: $F(2,32) = 16.694$; 14-year olds: $F(2,30) = 20.812$; 16-year olds: $F(2,26) = 13.769$; 18-year olds: $F(2,22) = 18.817$; 20-year olds: $F(2,26) = 46.439$, all ps < .001], as well as the main effect of dimension (with the exception of the ten-year olds). In all cases participants responded faster to colour (789.3, 691.0, 624.8, 524.4, 516.7, 441.2, 462.5 and 449.2 ms, for all age groups in ascending order), compared to orientation (858.6, 744.3, 655.8, 551.8, 552.8, 466.7, 488.9 and 470.4 ms, for all age groups in ascending order) signals [six-year olds: $F(1,19) = 4.825$, $p = .041$; eight-year olds: $F(1,13) = 18.813$, $p = .001$; ten-year olds: $F(1,16) = 4.042$, *n.s.* ($p = .062$); twelve-year olds: $F(1,16) = 27.626$, $p < .001$; 14-year olds: $F(1,15) = 144.074$, $p < .001$; 16-year olds: $F(1,13) = 23.769$, $p < .001$; 18-year olds: $F(1,11) = 18.232$, $p = .001$; 20-year olds: $F(1,13) = 17.219$, $p = .001$]. The faster processing of colour did not influence featural and dimensional previous-trial effects; in none of the age groups the interaction of inter-trial transition and dimension reached significance [six-year olds: $F(2,38) = 2.405$, *n.s.*; eight-year olds: $F(2,26) < 1$; ten-year olds: $F(2,32) < 1$; twelve-year olds: $F(2,32) = 3.026$, *n.s.*; 14-year olds: $F(2,30) = 1.486$, *n.s.*; 16-year olds: $F(2,26) = 2.807$, *n.s.*; 18-year olds: $F(2,22) < 1$ and 20-year olds: $F(2,26) = 2.965$, *n.s.*].

Planned simple contrasts revealed significant dimension-specific inter-trial effects: RTs increased when the target dimension in trial *n* had changed relative to *n-1* (sDdF vs. dD) for all age groups [eight-year olds: $F(1,13) = 8.926$, $p = .010$; ten-year olds: $F(1,16) = 11.226$, $p = .004$; twelve-year olds: $F(1,16) = 19.175$, $p < .001$; 14-year olds: $F(1,15) = 15.903$, $p = .001$; 16-year olds: $F(1,13) = 13.787$, $p = .003$; 18-year olds: $F(1,11) = 26.156$, $p < .001$; 20-year olds: $F(1,13) = 64.813$, $p < .001$], but the six-year olds, in which no dimension-specific target change effect was found [$F(1.19) = 1.217$, *n.s.*]. Interestingly, a significant feature-change effect was revealed for the six-year olds instead: RTs increased when the target feature in trial *n* had changed relative to trial *n-1* (sDsF vs. sDdF) [$F(1.19) = 12.106$, $p = .003$]. In none of the other age groups such a feature-specific target change effect was observed [eight-year olds: $F(1,13) = 2.227$; ten-year olds: $F(1,16) = 3.191$; twelve-year olds: $F(1,16) = 2.853$; 14-year olds: $F(1,15) = 3.509$; 16-year olds: $F(1,13) = 2.823$; 18-year olds: $F(1,11) < 1$; 20-year olds: $F(1,13) = 3.915$, all *n.s.*].

Within each inter-trial condition (sDsF, sDdF and dD) additionally UNIANOVAs and repeated contrasts were calculated in order to strengthen the obtained contrasts between the over all search RTs of all age groups. All UNIANOVAs with the between factor age (6, 8, 10, 12, 14, 16, 18, 20) revealed significant differences in RTs for all three conditions [sDsF: $F(7,116) = 37.775$, $p < .001$; sDdF: $F(7,116) = 42.666$, $p < .001$; dD: $F(7,116) = 37.765$, $p < .001$]. It was shown, that in all three

conditions RTs were markedly different between six- and eight [sDsF, sDdF, dD: all *p*s < .001], eight- and ten- [sDsF: $p = .027$; sDdF: $p = .024$; dD: $p = .024$], ten- and twelve- [sDsF: $p = .003$; sDdF: $p = .002$; dD: $p = .001$] and 14- and 16-year olds [sDsF: $p = .029$; sDdF: $p = .023$; dD: $p = .014$]. Between the other age groups, between the twelve- and the 14-, the 16- and the18-, and the 18- and the 20-year olds none of the contrasts was significant [sDsF: $F(7,116) = 37.775$; sDdF: $F(7,116) = 42.666$; dD: $F(7,116) = 37.765$, all *n.s.*].

There was no developmental effect found for the absolute size of the dimension-based previous trial effects (16.0 ms, 39.7 ms, 36.0 ms, 23.9 ms, 30.8 ms, 20.5 ms, 27.5 ms and 31.0 ms for all age group in their ascending order; $F(7,116) < 1$), for the feature-based previous trial effects, however, it was markedly more pronounced in the six- compared to the eight-year olds (45.0 ms, 14.7 ms; $F(7,116) = 3.376$, $p = .007$). Between the other age groups no significant size effect was found (11.0 ms, 6.7 ms, 11.8 ms, 6.2 ms, 1.6 ms and 9.0 ms for all participants aged ten and older, in ascending order; $F(7,116) = 3.376$, *n.s.*).

Age:	6	8	10	12	14	16	18	20
sDsF	824.0	694.6	621.0	525.6	516.6	443.0	465.5	443.5
sDdF	869.0	709.4	632.0	532.4	528.4	449.2	467.1	452.5
dD	885.0	749.1	668.0	556.3	559.2	469.7	494.5	483.5

Table 7: Mean RTs in the three inter-trial transition conditions: sDsF (same dimension same feature), sDdF (same dimension different feature) and dD (different dimension) for all age groups.

Discussion

Two main findings were observed in the present experiment. First, the results of the present study suggest that dimension-based (categorical) processing of visual stimuli is acquired in a critical developmental step between the ages six and eight. The main argument for this statement was found in the inter-trial analysis of the present data.

Second, there is further evidence for development of the processing mechanisms underlying visual selective attention. Support for this comes from the RT and the error analysis, suggesting critical developmental steps for sensory-motor skills up to age ten and for cognitive, search related processes between the ages of ten and twelve and again between the 14- and 16-year olds, proposing a full maturation in terms of visual search with the age of 16.

Category-/dimension-based processing. Overall, the participants aged eight and above replicated earlier results of dimension-based RT-costs and -benefits associated with changes and repetitions of the target-defining dimension/category (Müller at al., 1995; Found & Müller, 1996). There was a

marked RT increase for target dimension change transitions, whereby RTs in these age groups were not further expedited if the discrete feature within one dimension was repeated across trials. In other words, the dimension-based saliency signals sufficiently guided focal attention to the target location and a response was initiated fast by participants aged eight and above. By contrast, in the group of the youngest participants, children aged six years, no such RT-costs in association with the change of a target defining dimension, but the target feature, rather, was observed (45.0 ms compared to the mean RT increase of the other age groups of only 8.7 ms). The search performance was only enhanced, when the exact feature was repeated across trials. Crucially, there were no dimension-based previous-trial effects observed.

This RT pattern clearly shows, that participants aged eight and above were able to use categorical information in order to make a correct decision about the targets presence or absence respectively, whereas participants aged six performed the task on a feature-representational basis. In other words, in line with earlier literature (Bruner et al., 1966; Donnelly et al., 2007; Frith & Frith, 1978; Gerhardstein et al., 1999; Ross et al., 2005; Tversky, 1985) participants younger than eight were not able to classify individual object features to superior dimensional concepts in order to facilitate search for a singleton feature target. They processed perceptually highly distinctive feature information in a concrete fashion.

An additional analysis of the previous trial effect over the age groups revealed, that the absolute size of the dimension-based RT increase in cross-dimensional search did not significantly change across different ages. This supports the view that the ability to categorise is developed in a critical age, but that once, this behaviour is pronounced, no further development is taking place. The same holds true for the insignificant feature-repetition/-change RT differences. With the exception of the difference between six- and eight-year olds no further development of the effect was observed across age groups. Once the ability to process categories is evolved, there is no longer need to attentionally process featural representations in tasks like the one used in this experiment, at least.

Interestingly, the pattern of feature-based RT-costs and -benefits of the six-year olds suggests that similar to the weighted dimension-based saliency signal activation in older age groups, the actual feature activation/weight persist into a subsequent trial in terms of a feature-repetition RT-benefit. The critical age of six (age of school attendance) suggests that school, particularly the skills required for reading and writing, might influence the ability to use dimensional/categorical information (Tversky, 1985).

Sensory-motor versus cognitive development. In both tasks, the simple RT and the search task (in target absent as well as target present trials) RTs decreased with increasing age in a decelerated fashion. Comparable findings were reported in earlier experiments measuring RTs (Donnellly et al., 2007; Trick & Enns, 1998; see also Burack, Enns, Iarocci & Randolph (2000) for such an effect in a feature grouping experiment) and saccade latencies (Adler & Orprecio, 2006; Yang, Bucci & Kapoula,

2002) of children of different ages in comparison with adult observers. However, search RTs between the age groups were not all significantly different from each other. Only between the six- and the eight-, the eight- and the ten-, the ten- and the twelve- and the 14- and the 16-year olds RTs were accelerated markedly. Until now, the slowed RTs in young children were explained by ongoing motor maturation of sensory and motor pathways (Adler & Orprecio, 2006; Trick & Enns, 1998, Yang et al., 2002). This was replicated in the present experiment by means of a simple RT task, including only process components of sensory detection and response execution. Simple RTs indeed were substantially speeded across the three youngest age groups, explaining (or at least contributing to) the over all search RT decrease across these age groups. Note, that with regard to the assumptions of the DW account (Müller et al., 1995; 1996), the RTs in the age group of the six-year olds might be additionally slowed, by the requirement to access the level of feature representations.
However, the sensory-motor maturation cannot account for the significant expedition of RTs across the older age groups (between ten and twelve and 14 and 16). Thus it seems highly likely that between these age groups cognitive, search-related processes are further matured. These processes, reflected in the process components of signal discrimination and response selection were therefore eliminated by subtracting the simple RTs from the target-present search RTs (Donders, 1868, 1969). Indeed, the RTs associated with search-related mechanisms reached significance between the ten- and the twelve- and the 14- and 16-year olds and can therefore account for the RT decreases in older children / younger adults that cannot be explained by speeded sensory and motor processing. Interestingly, in children younger than ten, no such search-related maturation was observed, leading to the conclusion, that in this simple feature search acceleration of RTs across ages is either explained by sustained sensory-motor (up to age ten) or cognitive (between age ten and 16) maturation.

All in all, compared to search RTs of adult participants, the over all RTs of the younger children aged 14 and younger were significantly slower. In adult's visual search for a singleton feature targets mean RTs in target present trials usually range between 300 to 500 ms. In the older age groups, the 16-, 18- and 20-year olds, RTs indeed are at the upper boundary of the adult RT distribution. Mean RTs were between 472 and 489 ms. In the younger age groups the mean time to answer target present trials was found to range between 552 ms (14-year olds) and 879 ms (six-year olds). Thus it seems, that the final substantial decrease in RTs between the 14- and the 16-year olds has a special meaning by representing the borderline between premature and adult searchers, a result that is supported by the error distribution (see also below).

However, the analysis of the RTs for target present and absent trials replicated earlier findings (Donnelly et al., 2007; Trick & Enns, 1998) and revealed a well known pattern of faster RTs in target present compared to target absent trials. In all age groups observers allowed for some additional time before initiating a target-absent response in order to wait for a potential saliency signal to built up.

This seems to be a very robust effect, because Adler and Orprecio (2006) in their eye tracking study found faster saccades to stimulus present compared to stimulus absent displays even in very young infants between 84 and 114 days of age. Additionally, the ratio (difference) between absent and present RTs decreased across age groups, though not significantly as found in earlier studies (Donnelly et al., 2007; Trick & Enns, 1998). Interestingly Treisman and Gormican (1988) proposed, that target absent responses are additionally slowed in proportion of the naiveté (age?) of the observers.

Error rates were very low for all age groups, but similar to the RT distribution, decreased with increasing age in a decelerated manner. Therefore results were not contaminated by 'speed-accuracy tradeoffs'. One eye-catching result is the significant improvement in accuracy of the participants aged eight compared to their neighbouring age groups. Thus not only the six-, but also the ten- year olds had higher error rates. The effects of the detailed error analysis were not all significant, but the error distribution within the age groups generally supported the hypothesis, that from the age of 16 on, participants' performance in visual search becomes similar to adult's performance. In the three oldest age groups, the 16-, 18- and 20-year olds more errors in target present (miss) than absent (false alarm) trials were made. This error distribution replicates typical results found in adult observers. The effect was reversed for the six-, eight-, ten-, and twelve-year olds who made more false alarms than misses. The 14-year olds made an equal number of misses and false alarms, marking the turning point of the error distribution over the age groups.

In summary, in this experiment a simple feature search task was used in order to investigate children's ability to assign concrete feature representations to dimensional categories. The present data suggest that this ability is developed in a critical step between the age of six and eight. Additionally evidence for development of RTs and error distributions in feature search across childhood (age 6) and young adult age (age 16) was presented.

Experiment 6: Development of cognitive effects in visual search for a feature conjunction target

Purpose of the present study

The aim of the following experiment was to further distinguish between sensory-motor versus cognitive development in visual search. Therefore a conjunction task, in which the search-related process components due to higher complexity of the stimuli (higher distractor-distractor dissimilarity, higher target-distractor similarity) are expected to be more pronounced compared to simple feature search.

Method

Participants. 144 children and young adults aged between six and 20 years were tested by means of a feature conjunction search. As in the simple feature search, observers were divided in eight age groups: six- (N = 16, 8 female), eight- (N = 16, 6 female), ten- (N = 16, 10female), twelve- (N = 19, 13 female), 14- (N = 23, 13 female), 16- (N = 16, 10 female), 18- (N = 19, 18 female) and 20-year olds (N = 19, 16 female). All participants had normal or corrected-to-normal vision, all reported normal colour vision. None of the participants had ever taken part in a visual search experiment before. All observers were pupils in Zurich acquired through and tested by student assistants from the institute of developmental psychology of the University of Zurich. Student assistants received CHF 30.- an hour, participants received a snack after the session.

Apparatus, stimuli and task. The apparatus was the same as used for the simple feature search. Stimuli were apples defined in conjunctions of colour or size. All stimuli were approximately isoluminant (6.3 cd/cm²) and displayed against a dark grey background (0.7 cd/ cm²). Colour features were red and green, size features were big (0.9° x 0.9° of visual angle) or small (0.6° × 0.6° of visual angle).The four possible target and distractor types were big red, small red, big green and small green apples. The unique feature combination was the target; all other possible feature combinations were randomly assigned as being distractors. Three set sizes were used; displays contained either 7, 13 or 19 stimuli. For display size 7 the stimuli were arranged on one imaginary circle, including the central position with a maximal eccentricity of 5.7° of visual angle including the jitter. For display size 13 and 19, stimuli were arranged on two imaginary circles and the central position was included as well. Eccentricities of the inner and outer circle, respectively was including the jitter maximally 5.7° and 9° of visual angle. The spacing between the items was 1° of visual angle on the x- and the y-axis and positions were randomly jittered by a maximum of 0.5° of visual angle relative to the centre of the virtual matrix cells. Target locations were randomly selected out of any possible stimulus location in the display. Observers viewed the display from a distance of approximately 75 cm.

Procedure. Target-absent and -present trials were presented randomly. 60% of the experimental trials were target present, 40% target absent trials. The four target types were equally likely to appear in present trials. Participants were able to get familiar with the task by performing one exercise block of 50 trials. In Experiment 6 all observers of all age groups completed three experimental blocks, each consisting of 96 trials. Again, the blocks were additionally divided in three sub blocks to allow for breaks in order to avoid fatigue effects. At the start of each trial, instead of a fixation cross one of the stimuli was presented for 1000 ms in the centre of the display (central symbolic cue). In target present trials the presented item was always the target, cueing observers with 100% validity for the upcoming target, in target absent trials the presented item was randomly chosen out of the four stimulus types. The cue was followed by a 300 ms blank, before the experimental display appeared which then remained visible until response. The target-present response was given with the right control key (green cover), the target absent response with the left control key (red cover) of the keyboard. At the

end of every block observers received feedback about their accuracy and reaction times – participants older than ten by the monitor, participants aged six and eight verbally by the investigator. Generally participants aged six and eight were instructed, instructions for the older observers were displayed on the computer screen, but verbally repeated by the investigator in case the task was unclear. All observers were instructed to respond as quickly and accurately as possible. Again, after the visual search task, one block (of 72 trials) of a simple RT task was conducted from all participants. Observers were instructed to press the space bar as soon as they detected the onset of a search array on the display. Stimuli were exactly the same as in the search task, but observers did not discriminate target presence and absence.

Results

3.3% of all trials in the search task and 3.0% of all trials in the simple RT task were excluded from analysis for being either responded exceedingly slow or fast (anticipatory answers). RTs with more than three standard deviations from the mean were calculated for each age group and set size separately and were excluded from analysis (1.0% of the data in search task, 1.8% of the simple RT data). For the data analysis univariate analyses of variance (UNIANOVAs) and for multiple comparisons of the conditions Bonferroni corrections were used.

Errors. Error rates again were very low for all set sizes (7, 13 and 19) and all participants; for the six- (3.0%, 3.5%, 4.2%), eight- (1.8%, 2.4%, 1.8%), ten- (0.7%, 0.8%, 0.7%), twelve- (1.7%, 1.6%, 1.6%), 14- (1.7%, 1.5%, 1.7%), 16- (1.8%, 1.4%, 1.3%), 18- (0.9%, 0.9%, 0.9%) and 20- (1.1%, 1.1%, 1.1%) year olds. For each age group a repeated measures ANOVA was conducted with the factor set size (7 items, 13 items, 19 items). The main effect was significant for the six-year olds [$F(2,30) = 4.103$, $p = .027$], revealing a significant increase of the error rate with increasing set size. In all other age groups error rates did not differ significantly between the set sizes [eight-year olds: $F(2,30) = 3.221$; ten-year olds: $F(2,30) = 0.041$; twelve-year olds: $F(2,36) = 0.064$; 14-year olds: $F(2,44) = 0.420$; 16-year olds: $F(2,30) = 1.733$; 18-year olds: $F(2,36) = 0.068$; 20-year olds: $F(2,36) = 0.018$, all *n.s*]. Repeated contrasts, by comparing every age group with the corresponding next older one revealed the error rates between the six and the eight year olds to differ significantly from each other for set size 7 [$F(7,136) = 4.515$, $p = .031$] and 19 [$F(7,136) = 6.529$, $p < .001$], however, for set size 13, the error rates of the eight and the ten-year olds differed substantially from each other [$F(7,136) = 6.351$, $p = .004$]. None of the other age group differences reached significance.

In the detailed analysis of errors, misses (errors in present trials) and false alarms (errors in target absent trials) were analysed for each age group separately (Table 8) by repeated measures ANOVA with the factors error type (miss, false alarm) and set size (7 items, 13 items, 19 items). Only for the six-year olds the main effects of error type [$F(1,15) = 13.158$, $p = .002$] and set size [$F(2,30) = 3.880$, $p = .032$] were significant; they made more false alarms than misses and the error rate was increasing

with increasing set size. For the twelve- [$F(1,36) = 3.282$, $p = .049$] and the 20- [$F(1,36) = 4.090$, $p = .025$] year olds, the interaction reached significance, revealing that in both age groups more false alarms than misses were made for the set sizes 7 and 13, but that in set size 19 more misses were made relative to false alarms. For all other age groups none of the main effects or interactions was significant.

Repeated contrasts for misses and false alarms in each set size separately revealed significant differences in miss rates between the 16- and 18-year olds [$F(1,136) = 2.189$, $p = .024$] for set size 7 and between the eight- and ten-year olds in set size 13 [$F(1,136) = 2.650$, $p = .015$]. There were no differences in miss rates in set size 19. The false alarm rates differed significantly between six- and eight-year olds in all three set sizes [set size 7: $F(1,136) = 7.270$, $p < .001$; set size 13: $F(1,136) = 7.148$, $p = .004$; set size 19: $F(1,136) = 9.984$, $p < .001$] and additionally between eight- and ten-year olds in set size 13 [$F(1,136) = 7.148$, $p = .019$]. None of the other miss or false alarm rates differed significantly between the age groups.

Age		6	8	10	12	14	16	18	20
Miss rates [%]									
	Set Size 7	1.8	1.8	0.7	1.4	1.5	2.1	0.9	0.9
	Set Size 13	2.3	2.2	0.9	1.3	1.6	1.5	0.9	1.0
	Set Size 19	3.0	1.9	0.9	1.8	1.8	1.7	1.0	1.4
False alarm rate [%]									
	Set Size 7	4.8	1.8	0.8	2.1	2.0	1.5	0.9	1.3
	Set Size 13	5.1	2.7	0.7	2.1	1.4	1.3	0.9	1.2
	Set Size 19	6.0	1.8	0.5	1.4	1.7	0.7	0.7	0.7

Table 8: Miss and false alarm rates [%] for all age groups and set sizes.

Reaction times. The RT set size differences for target present and absent search trials (Table 9b) were each subject to eight independent repeated measures ANOVAs, one per age group with the main factor set size (7 items, 13 items, 19 items). For target present as well as absent trials all main effects of set size were significant [target present: six-year olds: $F(2,30) = 10.167$; eight-year olds: $F(2,30) = 17.880$; ten-year olds: $F(2,30) = 39.088$; twelve-year olds: $F(2,36) = 70.026$; 14-year olds: $F(2,44) = 41.189$; 16-year olds: $F(2,30) = 51.780$; 18-year olds: $F(2,36) = 110.005$; 20-year olds: $F(2,36) = 98.966$, all ps $< .001$ / target absent: six-year olds: $F(2,30) = 5.335$; eight-year olds: $F(2,30) = 14.728$; ten-year olds: $F(2,30) = 25.012$; twelve-year olds: $F(2,36) = 42.552$; 14-year olds: $F(2,44) = 62.041$; 16-year olds: $F(2,30) = 45.592$; 18-year olds: $F(2,36) = 72.579$; 20-year olds: $F(2,36) = 88.062$, all ps

< .001, with the exception of $p = .010$ for the six-year olds]. For all participants RTs increased with increasing set size.

Search RTs to target present, compared to target absent trials were analysed by means of three independent repeated measures ANOVAs with the within factor trial (absent, present) and the between factor age (6, 8, 10, 12, 14, 16, 18, 20) for each set size separately. All three main effects of trial [set size 7: $F(1,136) = 126.639$, $p < .001$; set size 13: $F(1,136) = 114.603$, $p < .001$; set size 19: $F(1,136) = 137.880$, $p < .001$] as well as all interactions of trial*age [set size 7: $F(7,136) = 10.067$, $p < .001$; set size 13: $F(7,136) = 6.807$, $p < .001$; set size 19: $F(7,136) = 5.585$, $p < .001$] were significant. In all set sizes target present trials were responded to faster than target absent trials, which was revealed by additional t-tests for the six- [set size 7: $t(15) = 4.139$, two-tailed $p = .001$; set size 13: $t(15) = 3.391$, two-tailed $p = .004$; set size 19: $t(15) = 3.484$, two-tailed $p = .003$], eight- [set size 7: $t(15) = 6.034$; set size 13: $t(15) = 6.260$; set size 19: $t(15) = 5.499$, all two-tailed $ps < .001$], ten- [set size 7: $t(15) = 5.187$; set size 13: $t(15) = 5.241$; set size 19: $t(15) = 5.429$, all two-tailed $ps < .001$], twelve- [set size 7: $t(18) = 5.529$; set size 13: $t(18) = 6.259$; set size 19: $t(18) = 5.587$, all two-tailed $ps < .001$], 14- [set size 7: $t(22) = 5.290$; set size 13: $t(22) = 5.552$; set size 19: $t(22) = 7.527$, all two-tailed $ps < .001$], 16- [set size 7: $t(15) = 4.201$, two-tailed $p = .001$; set size 13: $t(15) = 3.555$, two-tailed $p = .003$; set size 19: $t(15) = 4.095$, two-tailed $p = .001$], 18- [set size 7: $t(18) = 8.742$; set size 13: $t(18) = 5.643$; set size 19: $t(18) = 8.891$, all two-tailed $ps < .001$] and 20- [set size 7: $t(18) = 6.226$; set size 13: $t(18) = 6.102$; set size 19: $t(18) = 6.372$, all two-tailed $ps < .001$] year olds.

The slopes (search rate in ms/Item) and y-intercepts of target present and absent search functions were calculated for each age group and subject to four independent UNIANOVAs. It can clearly be seen, that the search slopes decreased with increasing age in target absent as well as target present trials (Table 9a). For both conditions the according UNIANOVAs revealed a significant effect of the between subject factor age (6, 8, 10, 12, 14, 16, 18, 20) [target absent: $F(7,136) = 2.169$, $p = .041$; target present: $F(7,136) = 6.495$, $p < .001$]. The search rate, the time observers needed to search one item in the display (ms/Item) decreased with decreasing age. However, repeated contrasts across age groups revealed no significant differences between the age groups for target absent slopes [$F(7,136) = 2.169$, *n.s.*] and for target present slopes. Only the difference between the six- and the eight-year olds was significant. The six-year olds were significantly slower than the eight-year olds [$F(7,136) = 6.495$, $p = .005$]. All other age groups did not differ substantially from each other in search slopes for target present trials. The two UNIANOVAs for target absent and present trial y-intercepts of the search functions both reached significance [target absent: $F(7,136) = 37.822$, $p < .001$; target present: $F(7,136) = 54.970$, $p < .001$]. The y-intercept decreased with increasing age (Table 9a), with the exception of the 12 year olds (see discussion). Repeated contrasts across age groups for target absent y-intercepts of the search functions revealed significant differences between the six- and the eight-year olds [$p < .001$] and the eight- and the ten-year olds [$p = .005$]. For target present y-intercepts repeated contrasts were substantial between the six- and the eight- [$p < .001$], the eight- and the ten- [$p = .001$],

the ten- and the twelve [p = .038] and the 14- and the 16- [p = .014] year olds, replicating a pattern of significance well known from the RT differences of the simple feature search task of Experiment 5. Exactly this distribution of significances was also found for the mean RTs to target present and absent search trials in all three set sizes; six independent UNIANOVAs with age as the between subject factor (6, 8, 10, 12, 14, 16, 18, 20) revealed significant differences in mean RTs to target present trials for set size 7 [F(7,136) = 65.862], set size 13 [F(7,136) = 65.818] and set size 19 [F(7,136) = 59.063] and in mean RTs to target absent trials for set size 7 [F(7,136) = 57.530], set size 13 [F(7,136) = 63.764] and size 19 [F(7,136) = 68.302] (all ps < .001). In general, mean RTs decreased with increasing age, however, repeated contrast across age groups in all six conditions revealed always the same pattern of significances; the six-year olds were markedly slower than the eight-year olds [target present: set size 7, set size 13, set size 19 / target absent: set size 7, set size 13, set size 19, all ps < .001], the eight-year olds were markedly slower than the ten-year olds [target present: set size 7: p = .001; set size 13: p = .007; set size 19: p = .007 / target absent: set size 7: p = .002; set size 13: p = .002; set size 19: p = .005], the ten-year olds were markedly slower than the twelve-year olds [target present: set size 7: p = .009; set size 13: p = .005; set size 19: p = .005 / target absent: set size 7: p = .010; set size 13: p = .005; set size 19: p = .001] and the 14-year olds were markedly slower than the 16-year olds [target present: set size 7: p = .006; set size 13: p = .009; set size 19: p = .011 / target absent: set size 7: p = .014; set size 13: p = .005; set size 19: p = .002]. Between the twelve- and the 14-year olds, between the 16- and 18- year olds as well as between the 18- and 20-year olds mean RTs in none of the six search conditions (target absent / present x set size 7 / 13 / 19) differed significantly.

Similar to Experiment 1, mean RTs of the search (only present RTs were included) and the simple RT task were compared by means of three independent repeated measures ANOVAs with the within factor task (choice RT, simple RT) and the between factor age (6, 8, 10, 12, 14, 16, 18, 20) for each set size separately. All three main effects of task [set size 7: F(1,136) = 1373.615; set size 13: F(1,136) = 1412.276; set size 19: F(1,136) = 1323.587, all ps < .001] as well as all interactions of task*age [set size 7: F(7,136) = 55.769; set size 13: F(7,136) = 53.853; set size 19: F(7,136) = 50.215, all ps < .001] were highly significant. In all set sizes simple RTs were markedly reduced compared to search RTs. The simple RT task mean RTs decreased with increasing age in a decelerated fashion similar to the search RTs (Table 9b) and an UNIANOVA confirmed this impression with a significant main effect for age [F(7,136) = 19.238, p < .001]. Significant RT differences between the age groups were evaluated by means of repeated contrasts: the six-year olds were significantly slower than the eight-year olds [p < .001] and the eight-year olds were significantly slower than the ten-year [p = .001]. RTs of the following age groups did not differ substantially from each other.

This is exactly the same distribution of significances as found in the simple RT task of Experiment 5. Again, as in Experiment 5, the simple RTs (sensory-motor RTs) were subtracted from the search RTs in order to filter out RTs associated with cognitive search-related factors (Table 9c). The cognitive RTs UNIANOVAs for each set size unveiled significant effects of age [set size 7: F(7,136) = 55.769;

set size 13: $F(7,136) = 53.853$; set size 19: $F(7,136) = 50.215$, all ps < .001], and repeated contrasts uncovered six-year olds to be slower than eight-year olds [set size 7, set size 13, set size 19, all ps < .001], eight-year olds to be slower than ten year olds [set size 7: $p = .008$; set size 13: n.s. ($p = .067$); set size 19: $p = .046$], ten-year olds to be slower than twelve-year olds [set size 7: $p = .002$; set size 13: $p = .001$; set size 19: $p = .001$] and 14-year olds to be slower than 16-year olds [set size 7: $p = .004$; set size 13: $p = .008$; set size 19: $p = .009$]. See also Figure 19 for an illustration of all target present RTs (search, simple and cognitive RTs) inclusive substantial RT differences across age groups for all three set sizes 7 (a), 13 (b) and 19 (c) separately.

Age	6	8	10	12	14	16	18	20
a) Search RTs								
Target present								
Set Size 7	1808.1	1215.0	936.7	727.3	806.1	596.9	550.2	606.3
Set Size 13	1941.6	1257.2	1019.3	780.9	854.0	640.6	606.4	653.9
Set Size 19	2106.1	1388.7	1111.8	834.7	922.9	681.3	637.5	715.5
Search function								
Slopes	25	15	15	9	10	7	7	9
y-intercepts	1629.1	1098.7	833.0	664.6	734.4	548.1	503.4	540.3
Target absent								
Set Size 7	2183.3	1425.6	1084.4	806.0	898.5	642.9	615.9	668.2
Set Size 13	2274.4	1504.9	1168.0	874.3	971.9	693.4	666.8	724.5
Set Size 19	2473.4	1641.3	1323.5	964.7	1073.9	752.6	741.6	798.1
Search function								
Slopes	25	18	21	13	15	9	11	11
y-intercepts	1996.2	1290.2	933.0	709.7	791.5	577.4	538.7	589.5
b) Simple RTs	427.0	333.8	260.2	281.1	242.5	236.8	254.0	256.1
c) Cognitive RTs								
Set Size 7	1381.1	881.2	676.5	446.2	563.6	360.1	296.2	350.1
Set Size 13	1514.5	923.5	759.0	499.8	611.5	403.9	352.4	397.8
Set Size 19	1679.0	1055.0	851.5	553.7	680.4	444.6	383.5	459.4

Table 9: Mean RTs (in milliseconds) of all eight age groups for target present and absent trials of the feature search task and search function slopes and y-intercepts of all set sizes (a). Mean RTs of the simple RT task (b) and mean RTs associated with cognitive factors (c) revealed by subtracting b from a (present trials).

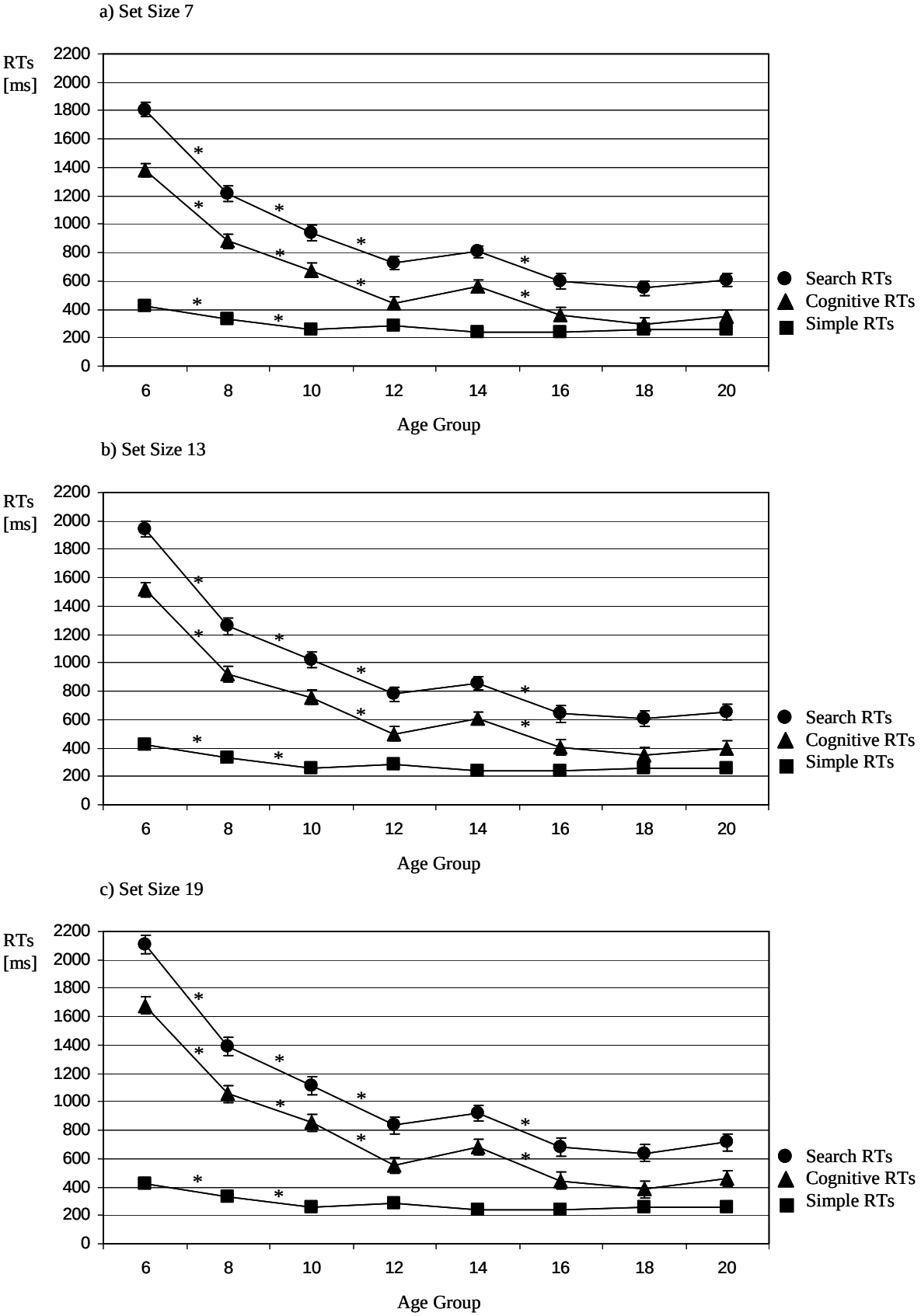


Figure 19: Mean search, simple and cognitive RTs (in milliseconds) of all eight age groups for target present trials only in all three set sizes a) 7, b) 13 and c) 19. Mean RTs associated with cognitive factors were revealed by subtracting simple from search RTs. Stars (*) indicate significant RT differences between the according age groups.

Inter-trial effects. In the inter-trial analysis three types of inter-trial transitions were of interest: no feature change (both target defining features are repeated across trials, i.e. a big red apple preceded by a big red apple), one feature change (one of the target defining features changed across trials, the other one was repeated, i.e. a big red apple preceded by a small red apple) and two feature changes (both target defining features changed across trials, i.e. a big red apple preceded by a small green apple). Eight repeated measures ANOVAs with the factors inter-trial transition (noFC, oneFC, twoFC) and set size (7 items, 13 items, 19 items) were conducted separately for each age group. The main effect of set size was substantial for all age groups as can be concluded from the RT set size analysis (see above). For the six-year olds, the main effect of inter-trial transition was significant [$F(2,30) = 4.629$, $p = .018$]. Within-subjects contrasts revealed a significant increase in RTs for feature-change transitions (noFC → oneFC; $F(1,15) = 6.699$, $p = .041$), whereas RTs were not additionally slowed for two feature change transitions (oneFC → twoFC; $F(1,15) < 1$). For the eight-year olds, there was also a significant main effect of inter-trial transition [$F(2,30) = 3.930$, $p = .030$], but within-subjects contrasts revealed no reliable RTs effects of feature change or repetition transitions (noFC → oneFC; $F(1,15) = 1.191$; oneFC → twoFC; $F(1,15) = 3.640$, both *n.s.*). For the twelve-year olds the main effect of inter-trial transition was significant [$F(2,36) = 8.465$, $p = .001$] and within-subjects contrasts unveiled RT-increases for feature-change transitions to be significant (noFC → oneFC; $F(1,18) = 14.364$, $p = .003$), but not for two feature change transitions (oneFC → twoFC; $F(1,18) < 1$). The main effect of inter-trial transition was not significant for the 14-year olds, but the interaction was [$F(4,88) = 3.211$, $p = .016$], but additional t-tests revealed no significant results. There was also a substantial main effect of inter-trial transition for the 16-year olds [$F(2,30) = 11.475$, $p < .001$], but for this age group within-subjects contrasts showed no reliable RT-benefit for feature-repetition transitions (noFC → oneFC; $F(1,15) = 3.983$, *n.s.*) but RTs were significantly slowed for two feature change transitions [oneFC → twoFC; $F(1,15) = 21.048$, $p < .001$]. For the 18-year olds, the effect again was the other way round. The inter-trial transition main effect was substantial [$F(2,36) = 6.442$, $p = .004$], but within-subjects contrasts again unveiled RTs to be mainly slowed by any feature change across trials [noFC → oneFC; $F(1,18) = 6.783$, $p = .036$], independent of whether the second feature changed as well [oneFC → twoFC; $F(1,18) = 2.671$, *n.s.*]. Finally for the 20-year olds, the main effect [$F(2,36) = 6.683$, $p = .003$] as well as the interaction [$F(4,72) = 4.207$, $p = .004$] was found to be substantial. Both within-subjects contrasts failed to reach significance (noFC → oneFC; $F(1,18) = 3.086$; oneFC → twoFC; $F(1,18) = 2.612$, both *n.s.*). Additional t-tests revealed a one feature change RT-cost for set size 7 [$t(18) = 2.291$, two-tailed $p = .034$] and a two feature change RT-cost for set size 19 [$t(18) = 3.422$, two-tailed $p = .003$] to be significant. All other interactions were not reliable.

Discussion

The most important finding of the present experiment is the distribution of target present search RTs, simple RTs and RTs associated with cognitive factors. In general RTs in all three conditions decreased with increasing age; an effect that was also observed in the y-intercepts of the search functions. The overall RT results of the Experiment 5 (e.g. Adler & Orprecio, 2006; Donnellly et al., 2007; Trick & Enns, 1998; Yang et al. 2002) were replicated. Exactly as in Experiment 5 only the six- and the eight-, the eight- and the ten-, the ten- and the twelve- and the 14- and the 16-year olds differed markedly in their search RTs. Note, that the 14-year olds in the conjunction search seem to step out of line. Whereas in the target present search RTs of the simple feature search of Experiment 5, RTs for the 14-year olds were only little increased compared to those of the twelve-year olds (+6.5 ms) in the conjunction search, this increase was way more pronounced, though not significant, across all set sizes (set size 7: +78.8 ms; set size 13: +73.1 ms; set 19: +88.1 ms). Therefore the significant differences between the 14- and 16-year olds in the target present search RTs, as well as in the RTs associated with cognitive factors (additive effect) and the y-intercepts of the search functions in Experiment 6 have to be interpreted carefully.

However, following the logic of Donders (1868, 1969) and as in Experiment 5 the overall RTs of the search task were divided into sensory-motor (simple RT) and search-related (choice RTs – simple RTs) components. In both simple RT tasks of Experiment 5 and 6 only sensory-motor process components not including stimulus and response discrimination were measured, independent of the different stimulus material. It was therefore expected to find significant motor and sensory RT accelerations between the three youngest age groups again in Experiment 6 comparable to Experiment 5. Indeed, the sensory-motor RTs were speeded for eight- compared to six- and again for ten- compared to eight-year olds, strengthening the hypothesis, that up to age ten sensory-motor pathways are still in formation, whereas after age ten no further development of these functions may be expected. This is exactly what was concluded from the findings of Experiment 5 as well.

At the same time, due to the greater complexity of a conjunction search task compared to a simple feature search task, it was expected as well to find stronger modulations of the RTs associated with cognitive factors. The contingent of search-related factors was expected to be more pronounced in Experiment 6. Indeed, it seems that in the feature conjunction search of Experiment 6 the decrease in search RTs for the three youngest age groups is not solely explained by motor maturation as it was found in Experiment 5. There is ongoing cognitive development present between six- and ten-year olds (significant RT differences between these age groups in the cognitive RTs). This hypothesis is in contrast with for example Adler and Orprecio (2006) and Trick and Enns (1998), who explained the slower search RTs in young children as being caused by insufficiently matured sensory and motor pathways solely. Clearly in the present experiment cognitive RTs were speeded between the six-, eight and ten-year old children reflecting ongoing cognitive maturation.

In all age groups set size effects were markedly pronounced. RTs increased with increasing set size for all age groups. And although in all age groups target absent trials were responded to slower than target present trials concerning the search function slopes (search rate in ms/Item) and y-intercepts, age differences were obtained. Clearly the search slopes decreased with increasing age (e.g. Donnelly et al., 2007; Gerhardstein et al., 2001; Trick & Enns, 1998), although this decrease was only revealed to be substantial between the six- and the eight-year olds. In subsequent age groups no further significant boost of the search rate was observed. This can be interpreted as evidence, that the search mechanisms for all age groups older than six must have been similar and that only the speed of the response, as reflected in the y-intercepts of the search functions differed between age groups.

This would stand in contrast to the findings of Donnelly et al. (2007) who detected search rates to be inversely related to age and the ratio between target present and absent trials to decrease with increasing age. It would also stand in contrast to the distribution of cognitive and sensory-motor RT differences over the age groups, speaking in favour for ongoing cognitive development of search strategies in this experiment.

However, by closer investigation one might also take into account a top-down modulatory effect for the somewhat levelled search slopes across age groups. The search slopes for target present trials of participants older than ten were not above 10 ms/item, which is the conventional criterion for serial search. This might be due to the applied trial-by-trial cueing in the present task. Participants older than ten seem to have used the cue properly as a help in order to detect the target in a more parallel scanning process. However, in target absent trials the cue was not of help and therefore search slopes (with the exception of the 16-year olds) were above the 10 ms/item threshold indicating a successive serial item per item search.

Interestingly it seems that the three youngest age groups were not (or less) able to use the cue information in order to boost target detection. They produced high search rates in target present trials as well, and between the six- and eight-year olds this effect was even significant. Note that for a serial feature conjunction search, typically a 2:1 ratio between the search function slopes for target absent and present search, respectively, is expected. This ratio reflects search to be self-terminating in target present and exhaustive in target absent trials. In the present data the target absent-present slope ratios were 1.0, 1.2, 1.4, 1.4, 1.5, 1.3, 1.6, 1.2 for six- eight-, ten-, twelve-, 14-, 16-, 18- and 20-year olds, respectively, suggesting, however, that target absent search was not completely exhaustive in nature, but at least more effortful than target present search. In contrast to all other age groups the six-year olds produced target absent and present search slopes that were equal (ratio of 1.0) and the target present search slope was significantly increased compared to the target present search slopes of the other age groups. This suggests, that six-year olds, not only searched serial in target absent and present trials, but that they searched exhaustively in both, target absent and present trials (since search could not have been self-terminating in target absent trials). This implicates, that observers of this age group must have missed the target in several trials when checking one display item after the other.

Statistically they must have found the item after having checked half of the display items. Since the cue seemed to be useless in the age group of the six-year olds, together with the pre-knowledge of the first experiment, that six-year olds process search items on the basis of their featural identity rather than on any dimension-based saliency signal, one could conclude, that only after having checked all of the display items (in target present and absent trials) six-year old observers were able to decide whether or not a target (a unique combination of features) was present in the display. Eventually they re-investigated already searched item locations marked as potential target locations, post-selectively after having ensured the uniqueness of the marked items. Note that numerically in target present search trials the six-year olds were about 593 ms, 684 ms and 717 ms slower compared to the eight-year olds in set sizes 7, 13 and 19, respectively. The numerical differences of RTs for all other age groups are markedly smaller (278 ms, 237 ms and 277 ms for example as the next highest RT difference of the eight- and the ten-year olds in set sizes 7, 13 and 19). Obviously the six-year olds must have searched with a completely different strategy compared to all other age groups. This very well fits Gerhardstein et al.'s (2001) finding of their children participants hunting through the displays manually in order to not just perceptually detect, but eventually post-selectively ensure target identity. The eight- and the ten-year olds seemed to be able to make more use of the cue, though still not as efficient as participants aged twelve and older. They were still producing serial search slopes in target absent as well as target present trials. The present slopes were compared to the slopes in absent trials still quite similar (eight-year olds: ratio 1.2; ten-year olds: ratio 1.4), though already more similar to those of the older age groups, especially for the ten-year olds. All together, this inability (six-year olds) or reduced ability (eight- and ten-year olds) to make use of the supportive information of the cue might exactly be the cognitive maturation reflected in the cognitive search-related RTs revealing significant differences between these three age groups.

In this experiment as well, error rates were extremely low for all age groups, with the exception of the six-year olds, who produced significantly more errors compared to the other age groups. Especially, they were the only age group with increasing error rates dependent of set size. This can also be explained by the disadvantage of this age group to use the cue as an effective tool to not just faster, but also more accurate detection of the target. The more items were presented, the more difficult was the search, especially without the information of the cue and conclusively the more errors were made. Clearly, since not only RTs but also error rates are increased in this age group, none of the effects are contaminated by speed-accuracy tradeoffs. In the other older age groups participants were able to set themselves for the upcoming target successfully reflected by higher accuracy as well as accelerated speed.

In summary, in this experiment it was shown by means of a feature conjunction search task that in young ages as well cognitive maturation is going on in terms of visual search processes and that acceleration of search RTs in young children is not only due to sustained motor development. Further the critical development step between the age of six and eight was further highlighted by showing that with the age of eight cued information about the upcoming target identity is more likely to be used and after age ten is perfectly implemented in search and successfully used in order to facilitate difficult search. With age six on the other hand, the cued information remains completely unexploited.

General conclusion of Experiment 5 and 6

The results of these experiments clearly show developmental effects in the mechanisms underlying visual search for feature and feature conjunction targets.

First of all, overall search rates in both search tasks, as well as simple RTs decreased continuously with decreasing age. With the age of 16 this decrease seems to be completed and search RTs resemble those of adult observers. Second, in both search tasks, children as well as adults took some extra time in order to respond to target absent compared to present trials, but with increasing age, the target absent-present ratio decreased. Third it was shown, that the search RTs to feature as well as feature conjunction singletons are modulated by ongoing maturation of sensory-motor on the one and cognitive search-related processes on the other hand. It was additionally shown that these two processing components are involved in the development of feature and feature conjunction search with varying contingent. Fourth, six-year old participants were found not to be able to use categorical information in order to facilitate search, but rather that feature identities are processed. After age six, category-/dimension-based processing is completely achieved. Fifth and least, six-year old participants seem to be unable to use top-down information in order to facilitate search. The ability to implement pre-cued information in terms of an effective mind set guiding search seems to be developed beyond age six and across ages of eight and ten in order to be matured with twelve.

7. Affect modulates feature-based attentional selection

According to Pessoa (2008) “the current view of brain organisation supports the notion that there is a considerable degree of functional specialisation and that many regions can be conceptualised as either ‘affective’ or ‘cognitive’” (p. 148). But this is a problematic view, since “complex cognitive-emotional behaviours have their basis in dynamic coalitions of networks of brain areas, none of which should be conceptualised as specifically affective or cognitive.” (Pessoa, 2008, p. 148).
Indeed, some researchers have provided evidence for such a coalition between affect and selective attention.

Generally, it was proposed that attentional selection might be influenced by the current affective state of the observer (Derryberry & Tucker, 1994). It was shown, that participants in a positive mood tend to process visual material in a global fashion, whereas participants in a negative mood rather focus on local visual information (Basso, Schefft, Ris, & Dember, 1996; Gasper & Clore, 2002). Gasper and Clore (2002) for instance showed that participants in sad mood relative to happy mood were less likely to classify geometric figures on the basis of their global features, but focused on local information (small figues inside the global figures). It is to note, though, that the results of these studies were usually interpreted in the framework of affect-as-information theories (Schwartz & Clore, 1983, 1988), explaining the changed focus of attention as a cognitive bias, rather than a phenomenon of interest in itself.

However, in general, it is accepted, that negative affective states are accompanied with a constriction of the attentional focus (Easterbrook, 1959) and that this narrowing of attention (Derryberry & Reed, 1988) happens on the expense of peripheral information encoding (Christianson & Loftus, 1990). This assumption is very much in line with Lavie and Tsal (1994; see also Lavie, 1995, 2005), who found irrelevant distractors in a flanker task (Eriksen & Eriksen, 1974) not to be attended to in a high perceptual load condition that caused a narrowed attentional focus.
In contrast with the proposed tunnel-vision of observers in a negative affective state the attentional scope is thought to be enhanced for observers in a positive affective state (Derryberry & Tucker, 1994; Rowe, Hirsh, & Anderson, 2007). Rowe et al. (2007) induced their participants with positive (happy), negative (sad) and neutral mood and presented them with a flanker task (Eriksen & Eriksen, 1974). As predicted by the assumption of an enlarged attentional focus for positive affect, in the happy condition the distractor incompatibility effect was markedly increased in the happy compared to the neutral and sad condition. This is, in the happy condition, the identification of the central target letter suffered more from the presence of incompatible distractors compared to the sad and neutral groups – in the happy condition, the focus of attention was wide (e.g. LaBerge, 1983), the incompatible distractors were within the spatial focus (spotlight) of attention and therefore processed (e.g.Eriksen & Eriksen,

1974; Posner, 1988), in other words relevant information was filtered late (e.g.Lavie, 1995, 2005; Lavie & Tsal, 1994) and therefore the flankers in this task impaired / slowed target identification. On the other hand, in the sad condition, the focus of attention was narrowed, the incompatible distractors were outside of the focus of spatial attention and therefore not processed, the relevant information was filtered early and there was no interference by the flanker letters observed. The same pattern was also found for the neutral condition which conclusively was free to optimally set the focus of attention in order to properly solve the task. Critically, under conditions of far flankers (increased distance between flankers and target) there were still slowed RTs for the happy conditions, whereas the incompatibility effect was abolished for the neutral and sad groups. These results clearly showed an impairment of spatial selective attention under positive affect and Rowe et al. (2007) suggest, that "positive moods […] facilitate tasks requiring a more global and encompassing style of information processing […], but impair those calling for a narrow, focused style, such as selective visual attention" (p. 386).

Experiment 7: Modulating feature-based attentional selection by observer's affect

Purpose of the present study

Until now, the influence of observer's emotions on feature-based attentional selection has never been investigated. If anything the current literature focuses on space- (e.g. Rowe et al., 2007) or object-based (Basso, Schefft, Ris, & Dember, 1996; Gasper & Clore, 2002) attentional selection. In the present experiment it was aimed to investigate the influence of observer's emotional states on feature-based selection in visual search for a feature singleton. Due to the lack of any reference literature, the approach in the following experiment is rather exploratory in nature. Participants in this experiment were induced with either a positive, negative or neutral (control condition) emotions and RTs, error rates and inter-trial effects were compared across groups.

In line with earlier findings it was expected to observe a reduced processing speed on the one hand (for reviews see Christensen, Griffiths, Mackinnon, & Jacomb, 1997; Veiel, 1997) and a somewhat constricted (narrowed) attentional focus (Derryberry & Reed, 1988; Easterbrook, 1959) on the other hand in the negative emotion compared to the positive emotion and neutral baseline condition. Regarding the first it was hypothesised to find markedly slower RTs in the negative compared to the neutral condition. Concerning the latter and in line with Lavie and Tsal (1994; see also Lavie, 1995, 2005) one could conclude, that with a narrowed focus of attention participants in the negative mood condition would process the target on a deeper level compared to participants in the neutral and positive condition. The narrowed focus might cause early filtering of the relevant information and all available processing capacity would be used in order to identify the target rather than just to detect it.

If search mechanisms would be modulated in such a way, feature- rather than dimension-based inter-trial effects should occur in a cross-dimensional feature search. Spoken with the metaphor of a zoom-lens and similar to Christianson and Loftus (1990), attentional processing could be completely restricted to the target item and distractor elements might be excluded from the spotlight. In case of very strong effects this would hinder target detection on the basis of a saliency signal (similar to the single item condition of Experiment 1 of this PhD), since there would be no contrast between target and distractors. In this case, observers would identify rather than simply detect the target in order to give an accurate answer and feature-specific previous-trial effects would be likely to occur in the negative compared to the neutral and positive condition.

Regarding the search performance of observers in a positive emotional state, it was assumed to find a similar pattern of results as for participants in the neutral control condition. First of all, positive emotion induction in general is less effective than negative emotion induction, simply, because there rarely is such a thing as a neutral mood; in other words, neutral mood always tends to go in a more positive direction (Isen, 1984; see also Bandura, 1977). Second, if as hypothesised, positive mood is associated with an enhanced focus of attention (Rowe et al., 2007; Derryberry & Tucker, 1994) or a more global and holistic processing mode (Basso, Schefft, Ris, & Dember, 1996; Gasper & Clore, 2002), for a simple feature search there would be a ceiling effect. No matter to what supplementary extend a positive emotional state could enlarge the focus of attention (LaBerge, 1983) the filter of the system is still only as early or late as required by the perceptual load of the task at hand (Lavie, 1995, 2005; Lavie and Tsal, 1994). In a simple feature search, a task with low perceptual load (high distractor-distractor similarity; low target-distractor similarity; Duncan & Humphreys, 1989), the spotlight of attention might be expanded over all irrelevant (distractor) elements, since they are not thought to interfere with the target, no slowing of search is expected (as in the flanker experiment of Rowe, et al (2007) for instance). But compared to the neutral observers there is also no further expediting of target detection expected, since search for a feature singleton will always be parallel across display items, independent of set size. Therefore between neutral and positive emotion induced participants no substantial differences in RTs, error rates or inter-trial effects are expected.
In summary, space-based attentional selection of a target is expected to differ between the negative on the one hand and the positive and neutral condition on the other hand. Since each feature in the visual field occupies a certain location, there are also differences in the feature-based selection of the target expected between these conditions.

Terminology: There is quite some debate about whether induced affective states are correctly referred to as emotions or mood. Emotions are seen to be strong, but short affective events compared to mood, which in turn is thought to be a weaker, but persistent affective state.

In the present experiment with regard to the applied induction method and the relatively short duration of the induced affects, consistently the term emotion will be used instead of mood.
Usually in emotion induction studies the induced mood states are described with exact emotion-features. Participants in negative conditions might be sad, angry or frightened participants, whereas in positive conditions participants would be described as happy, for instance. Due to the lack of a detailed emotional state control in this experiment (participants only rated their sadness and happiness, respectively on a dichotomy scale) it was decided to refer to the groups as the negative, positive and neutral condition. The treatment check in this experiment showed that negative and positive emotions were successfully induced, but whether solely happy and sad emotion and no other affects (anger, fear, disgust...) were co-induced was not reliably checked.

Method

Participants. 60 observers, 20 per emotion induction condition participated in this experiment (positive emotion: 16 female, age range 19 to 29 years, median age 23.3 years; negative emotion: 16 female, age range 19 to 29 years, median age 22.5 years; neutral emotion: 16 female, age range 19 to 38 years, median age 24.8 years). All participants had normal or corrected-to-normal vision and had accurate colour vision. Participants were paid at a rate of CHF 10 per hour or received course credits. All observers were completely naïve as to the purpose of the emotional modulation of attentional selection; none of them had previous experience with visual-search experiments.
Apparatus, stimuli, task. In this experiment, the emotion induction condition was tested between subjects. All 60 participants, independent of emotion induction responded to exactly the same task and stimuli.
The experimental display comprised of a 7 × 7 item array of (search) items. Each cell of the virtual rectangular grid subtended 2.2° of visual angle in height and width. Item positions were slightly jittered vertically and horizontally by a maximum of 0.6° of visual angle relative to the cell centre. Minimum (and maximum) distance (measured as the distance between centres of gravity) between display items was 1.1° (3.3°) both horizontally and vertically. Distractor items were a homogenous green vertical bars (target absent trials), the to-be-searched target (target present trials) was a features singleton defined by colour (a red or blue vertical bar) or orientation (green 45° left- or right-tilted bar relative to the vertical). The target location was randomly chosen out of the inner 5 × 5 grid cells, in order to equate local feature contrast effects (observers were not informed about the restriction). All display items subtended approximately 0.9° of visual angle in height and 0.2° in width and were coloured in isoluminant green (CIE x,y chromatic coordinates 0.311, 0.578; luminance 1.6 cd/m²), red (CIE 0.596, 0.358; 1.6 cd/m²) or blue (CIE 0.148, 0.065; 1.6 cd/m²) and presented on black screen background. The entire display subtended between 16.0° of visual angle vertically and horizontally. Stimulus presentation, timing, and response recording were controlled by a Pentium PC running under the Windows XP operating system and using the “Cogent 2000” toolbox

(www.vislab.ucl.ac.uk/Cogent/) for MATLAB (Mathworks, Inc.). Stimuli were presented at 100 Hz on a 19" CRT monitor (Phillips Brilliance P202), at a screen resolution of 1280 × 1024 pixels. Observes viewed the display from a distance of 70 cm. Observers responded by pressing one of the control (Ctrl) keys in the lower left and right parts of a standard keyboard placed at a comfortable distance on a table in front of the observer. Observers' task was to indicate, as quickly and accurately as possible, whether a target item was present in the display or not (right ctrl key for a target present, left ctrl key for a target absent answers).

Emotion was induced by the 'film plus instruction' method (Gerrards-Hesse, Spies, & Hesse, 1994; Westermann, Spies, Stahl, & Hesse, 1996). Participants watched approximately a three minutes film sequence and were additionally instructed to adopt the emotional state of the characters in the film. Films were chosen according to Rottenberg, Ray and Gross (2007) film ratings catalogue: for positive emotion induction participants watched a sequence from "When Harry met Sally" (Rob Reiner, July 21st 1989, USA), for negative emotion induction a sequence from "Return to me" (Bonnie Hunt, April 7th 2000, USA) and for a neutral emotion induction a non-commercial screen saver "Sticks" (available for download at: http://uweb.cas.usf.edu/mood/images/sticks.mov). Participants were randomly assigned to one of the emotion induction groups.

Procedure and timing. Prior to the actual experiment participants conducted an exercise block, 50 trials of the visual search, in order to get familiar with the task. Each trial started with the presentation of a fixation point (a circle with a diameter of approx. 0.2° of visual angle) for 570 ms; over this period, the luminance of the fixation marker increased gradually from background luminance to 1.6 cd/m² and then gradually decreased again to background luminance. The screen remained blank for a period of 200 ms after the disappearance of the fixation point, to avoid forward masking in the single-item condition. The response-relevant display consisted of the simultaneous onset of all items. Displays remained visible until the observer had responded target-present or target-absent, but maximally for 3000 ms. The response was followed by an inter-trial interval with a blank screen for 400 ms.

After the training, participants rated their natural emotion (initial mood - here the term mood is used in order to make sure that no emotion was induced at that time) on a 5-step emotion scale (1 = very sad, 2 = sad, 3 = neutral, 4 = happy, 5 = very happy). They watched the film sequence according to their emotion induction group and rated the film with respect to its emotional valence (1 = very sad film, 2 = sad film, 3 = neutral film, 4 = happy film, 5 = very happy film). After they had rated their own emotion again (induced emotion) on the same emotion scale as at the beginning of the experiment they began with ten blocks of the visual search task, which was exactly the same as in the training block. Each block consisted of 94 trials, giving a total of 940 experimental trials. Targets were presented in 60% of the trials (target-present trials); in the remaining 40%, no target, but only distractors were presented (target-absent trials). The definition of the target type (colour: red, blue; orientation: left, right-tilted), in target-present trials, was equally probable. Observers were free to take breaks between

blocks, but were not informed about their performance (RTs or error rates). The actual experiment took approximately 25 minutes to complete. At the end of the experiment again observers rated their emotion (final emotion) on the emotion scale as already used at the beginning of the experiment.

Results I

Exceedingly fast and slow RTs were excluded from analysis (0.9% of the trials of each emotion induction group). Additionally, RTs deviating from mean RT by more than three standard deviations were excluded from analysis separately for each participant and each of the four conditions (1.2% in the positive, 1.3% in the neutral and 1.8% of the trials in the negative emotion induction group). Data were analysed using univariate analyses of variance (UNIANOVAs) and repeated-measures analyses of variance (ANOVAs); Bonferroni correction was used for multiple comparisons of condition means where necessary.

Mood induction. The film sequences had to be rated on a 5-step scale with respect to its emotional valence (1 = very sad film, 2 = sad film, 3 = neutral film, 4 = happy film, 5 = very happy film). This rating was used as a material check. The material was rated as expected; the mean ratings of the positive, negative and neutral films were 4.5, 1.4 and 3.0, respectively.

The three emotion ratings (1 = very sad, 2 = sad, 3 = neutral, 4 = happy, 5 = very happy) of the observers about their own emotional state were submitted to separate one-way ANOVAs with three levels (initial mood, induced emotion, final emotion). The initial mood served as an affective baseline of each observer, which was rated prior to the actual experiment. The induced emotion was rated after participants had seen the film sequence and served as a treatment check. The final emotion ratings were collected at the end of the experiment and served as a duration measurement of the induced mood. In all three conditions the effect was significant; the three emotion ratings differed substantially from each other [positive condition: $F(2,38) = 11.159$, $p < 001$; neutral condition: $F(2,38) = 6.763$, $p = .003$; negative condition: $F(2,38) = 11.789$, $p < .001$]. Pair-wise comparisons first revealed, that the emotion induction had worked as expected (comparison initial mood with induced emotion): in the positive condition participant's emotion rating increased slightly, but significantly (initial mood: 3.7, induced emotion: 4.1 / $p = .050$), in the negative condition participant's emotion rating decreased markedly (initial mood: 3.4, induced emotion: 2.4 / $p = .001$) and in the neutral condition there was no difference between the two ratings (initial mood: 3.3, induced emotion: 3.2 / *n.s.*). The according films had induced a positive or a negative emotion in observers of the positive or negative condition, respectively, and the neutral film had not changed participant's initial mood. Second pair-wise comparison showed, that in all conditions the emotion was rated to have changed during the experiment (comparison induced emotion with final emotion): in the positive condition the emotion rating decreased (induced emotion: 4.1, changed emotion: 3.4 / $p = .003$), in the negative condition the emotion rating increased (induced emotion: 2.4, changed emotion: 3.1 / $p = .014$) and in the neutral

condition the emotion rating decreased little, but substantially (induced emotion: 3.2, changed emotion: 2.8 / p = .050). During the experiment the emotional states in all conditions had changed significantly. For none of the conditions this was expected, tough not surprising for the negative group, in which the effect can be explained by Eysen's (1984) 'mood repair' hypothesis. He showed, that participants in negative affective states try hard to 'repair' their mood, in order to get ride of negative feelings. However, due to the short duration of the experiment (approximately 25 minutes) the induced emotions in all conditions were expected to hold during the whole experiment.
Interestingly also the neutral participants rated their emotional state to have change to the more negative side of the scale during the experiment. Since visual search is not thought to have sad emotion inducing impact on observers this deteriorated rating of the neutral group (and possibly also of the positive group) can be taken as evidence that other negative emotions than just sadness influenced the ratings in the present experiment.
However, it is to note, that the participants of the positive and negative condition rated their emotional state to have dropped or to have increased to a neutral level again during the experiment and that participants in the neutral condition rated their emotional state to have decreased during the experiment below the initial mood state (comparison final emotion with initial mood / positive condition: 3.4 vs. 3.7, p = .030; negative condition: 3.1 vs. 3.4, *n.s.*; neutral condition: 2.8 vs. 3.3, p = .013).

Errors. Over all participants in the positive emotion condition (4.6%) made more errors compared to the negative emotion condition (3.4%). Error rates of observers in the neutral emotion condition were in between (3.9%). However, the overall error UNIANOVA revealed no significant effect of condition (positive, negative, neutral emotion) [$F(2,57) < 1$]. Mean error rates for target-absent (false alarms) and target-present trials (misses) trials were additionally subjected to a mixed ANOVA with the within factor error type (miss, false alarm) and the between factor condition (positive, negative, neutral emotion). The ANOVA revealed the main effects of error type to be significant [$F(1,57) = 23.682$, $p < .001$]. Overall significantly more false alarms (5.1%; 5.6% in the positive, 4.9% in the neutral and 4.7% in the negative condition) than misses (3.2%; 3.9% in the positive, 3.2% in the neutral and 2.5% in the negative condition) were made. The interaction between error type and condition did not reach significance [$F(2,57) < 1$].

Reaction times. Mean target present and absent RTs were analysed with repeated-measures ANOVAS with the factor trial (present, absent) for each condition separately. All three ANOVAs revealed the main effect of trial to be significant [positive condition: $F(1,19) = 23.673$; neutral condition: $F(1,19) = 72.027$; negative condition: $F(1,19) = 32.434$, all ps < .001]. In all three conditions, RTs to target absent trials were markedly slower compared to target present trials (positive condition: 441.6 ms vs.

405.6 ms, neutral condition: 467.8 ms vs. 422.4 ms negative condition: 545.3 vs. 470.8 ms for target absent vs. present trials, respectively).

Target present trials of each condition separately (positive, negative, neutral emotion) were subject to ANOVAs with the factor dimension (colour, orientation). All three ANOVAs calculated colour targets to be responded to substantially faster than orientation targets [positive condition: 393.5 ms vs., 417.7 ms, $F(1,19) = 78.438$; neutral condition: 410.8 ms vs. 434.0 ms, $F(1,19) = 102.816$; negative condition: 459.0 ms vs. 482.6 ms, $F(1,19) = 55.592$, all ps < .001].

In order to compare processing speed across emotion conditions, RTs to all target types (target absent RTs were included as an additional target type – absent) were analysed separately (Table 10) by an UNIANOVA with the between factor condition (positive, negative, neutral emotion). The effect of condition proved to be substantial [$F(2,57) = 8.986$, $p < .001$]. Additional multiple post-hoc tests showed RTs for each target type (including target absent trials) to be significantly slower in the negative compared to the neutral and the positive condition. RTs in the neutral condition were slower compared to RTs in the positive condition, but the difference was never significant (see Table 10 for ps).

	Emotion condition			RT-benefit,-cost $(p)_{(condition1,condition2)}$		
	positive (pos)	neutral (neu)	negative (neg)	RT$(p)_{(pos,neu)}$	RT$(p)_{(neg,neu)}$	RT$(p)_{(pos,neg)}$
Absent	441.6	467.8	545.3	± 26.2(n.s.)	± 77.5(.011)	±103.7(<.001)
Blue	397.0	415.1	463.3	± 18.2(n.s.)	± 48.3(.030)	± 66.3(.002)
Red	390.1	406.5	454.7	± 16.4(n.s.)	± 48.2(.024)	± 64.6(.001)
Left	418.8	436.8	484.2	± 18.1(n.s.)	± 47.4(.041)	± 65.4(.003)
Right	416.6	431.2	480.9	± 14.6(n.s.)	± 49.8(.028)	± 64.3(.003)

Table 10: RTs (in milliseconds) for each target type (blue, red, left- and right-tilted), including target absent trials separately for the three experimental conditions (positive, neutral, negative emotion) and RT-benefits and -costs across conditions including p values of multiple post-hoc tests.

Inter-trial effects. Feature- and dimension-based inter-trial transition effects were analyzed separately for the three conditions (positive, negative, neutral emotion) by repeated-measures ANOVAs, each with the factors inter-trial transition (same dimension same feature, sDsF; same dimension different feature, sDdF; different dimension, dD) and dimension (colour, orientation). See Table 11 for mean RTs for the three types of inter-trial transitions.

For all analyses, both main effects, the one for dimension [positive condition: $F(1,19) = 81.296$; neutral condition: $F(1,19) = 77.429$; negative condition: $F(1,19) = 56.584$, all ps < .001] as well as the one for inter-trial transition [positive condition: $F(2,38) = 64.131$; neutral condition: $F(2,38) = 96.709$; negative condition: $F(2,38) = 70.474$, all ps < .001] were significant. In all conditions and inter-trial

transitions, RTs were faster to colour than to orientation targets and the pattern of inter-trial effects was similar between colour and orientation targets, the interaction of dimension x inter-trial transition did not reach significance in none of the analyses [positive condition: $F(2,38) < 1$; neutral condition: $F(2,38) = 2.370$, *n.s.*; negative condition: $F(2,38) = 1.629$, *n.s.*].

Planned simple contrasts (see Table 11 for numerical differences and p-values) to follow up these effects in the various conditions showed that in all conditions there was a dimension-specific change effect: RTs were significantly slower when the target on trial *n* was defined in a different dimension relative to the target on trial *n*-1 [comparison dD vs. sDdF / positive condition: $F(1,19) = 41.852$; neutral condition: $F(1,19) = 106.925$; negative condition: $F(1,19) = 69.465$, all *p*s < .001]. In the neutral condition earlier results (Found & Müller, 1996) of non-significant feature-specific change effects were replicated: RTs were not substantially slower when the target on trial *n* was defined in a different feature relative to the target on trial *n*-1 [comparison sDsF vs. sDdF / $F(1,19) = 1.008$, *n.s.*]. In contrast in the positive as well as in the negative condition RTs were significantly slowed down when the target feature changed across trials [positive condition: $F(1,19) = 12.679$, $p = .004$; negative condition: $F(1,19) = 20.232$, $p < .001$]. Due to the small numerical difference between feature-repetition and feature-change trials (sDsF vs. sDdF) two additional UNIANOVAs compared the numerical RT-differences between dimension- on the one and feature-specific repetition- and change-costs and -benefits on the other hand between the three conditions. There was no effect of condition (positive, negative, neutral emotion) between dimension-based RT-cost and -benefits, respectively [$F(2,57) < 1$]. In all three conditions, positive (22.6 ms), negative (27.7 ms) and neutral (27.2 ms) emotion, a target dimension change across trials produced similar RT-costs. On the other hand the UNIANOVA analysing feature-based RT-costs and –benefits, respectively, obtained a significant effect of condition (positive, negative, neutral emotion) [$F(2,57) = 5.241$, $p = .008$]. Planned post-hoc comparisons showed, that only the feature-based RT-costs/-benefits of the negative condition (9.8 ms) were markedly different to the baseline RT-costs/-benefits of the neutral condition (1.6 ms; $p = .006$); the RT-costs/-benefits of the positive condition (5.7 ms) were not substantially different from the neutral condition ($p = .321$). However, the RT-costs/-benefits of the positive and the negative condition did not differ significantly either ($p = .346$).

	Inter-trial transition			RT-costs/-benefits$_{(change/repetition)}$		
	sDsF	sDdF	dD	$D_{(change/repetition)}$	$F_{(change/repetition)}$	p
Positive	378.2	383.9	406.5	± 22.6		< .001
					± 5.7	= .004
Neutral	393.7	395.3	422.5	± 27.2		< .001
					± 1.6	n.s.
Negative	434.8	444.6	472.3	± 27.7		< .001
					± 9.8	< .001

Table 11: RTs (in milliseconds) separately for the four experimental conditions for the three relevant inter-trial transitions; sDsF = same dimension, same feature; sDdF = same dimension, different feature; dD = different dimension. RT-cost and -benefits associated with D = dimension and F = feature -changes and –repetitions across trials.

Results II

The mood ratings of the participants clearly showed that the emotion induction was successful in all emotion groups. All films had induced the planned emotions in the observers with respect to their according emotion groups. Unexpectedly though, the emotional state of the observers in all emotion conditions had changed during the experiment, in such a way, that negative and positive observers rated their emotional state to have increased or dropped again, respectively to the neutral level during the experiment.

Therefore the relevant analyses of the RTs and the inter-trial effects were repeated, only including the first five blocks (first half) of the experiment under the assumption that the effects of emotion induction decreased gradually across the experiment. Note that the amount of inter-trial transitions was sufficient to investigate reliable inter-trial effects even if only half the experimental trials were analysed.

Reaction times. For the first five blocks of the experiment the results of the processing speed did not change. RTs to all target types (target absent RTs were again included) separately (Table 12) were analysed by an UNIANOVA with the between factor condition (positive, negative, neutral emotion), which revealed a substantial effect of condition again [$F(2,57) = 8.296$, $p = .001$]. Multiple post-hoc tests showed RTs to be significantly slower in the negative compared to the neutral and the positive condition. The RTs of the neutral condition were slower, though not markedly than the RTs of the positive condition (see Table 12 for *p*s).

	Emotion condition			RT-benefit,-cost (p)$_{(condition1,condition2)}$		
	positive (pos)	neutral (neu)	negative (neg)	RT(p)$_{(pos,neu)}$	RT(p)$_{(neg,neu)}$	RT(p)$_{(pos,neg)}$
Absent	451.7	487.1	570.8	± 35.4(n.s.)	± 83.7(.022)	±119.1(.001)
Blue	403.9	426.1	481.8	± 22.2(n.s.)	± 55.7(.024)	± 78.0(.001)
Red	396.9	416.7	471.4	± 19.8(n.s.)	± 54.7(.025)	± 74.5(.001)
Left	428.2	449.4	501.5	± 21.2(n.s.)	± 52.1(.045)	± 73.3(.002)
Right	422.5	439.2	495.9	± 16.7(n.s.)	± 56.6(.027)	± 73.4(.003)

Table 12: RTs (in milliseconds) for each target type (blue, red, left- and right-tilted), including target absent trials separately for the three experimental conditions (positive, neutral, negative emotion) and RT-benefits and -costs across conditions including p values of multiple post-hoc tests. Only the first five blocks (first half) of the experiment were analysed.

Inter-trial effects. The same repeated-measures ANOVAs from Results I were conducted analysing feature- and dimension-based inter-trial effects separately for the three conditions (positive, negative, neutral emotion). The factors were inter-trial transition (same dimension same feature, sDsF; same dimension different feature, sDdF; different dimension, dD) and dimension (colour, orientation). See Table 13 for mean RTs for the three types of inter-trial transitions.

In all three conditions the main effects for dimension [faster processing of colour / positive condition: $F(1,19) = 71.631$; neutral condition: $F(1,19) = 40.505$; negative condition: $F(1,19) = 40.690$, all ps < .001] and inter-trial transition [positive condition: $F(2,38) = 34.682$; neutral condition: $F(2,38) = 42.509$; negative condition: $F(2,38) = 40.335$, all ps < .001] were significant. Additionally in the neutral group the interaction of dimension x inter-trial transition reached significance [$F(2,38) = 5.595$, $p = .007$], due to the faster processing of colour targets; the pattern of RTs in the dimension- and feature-based inter-trial transition effects was not influenced. In the positive and negative conditions the interaction was not substantial [positive condition: both Fs(2,38) < 1].

Planned simple contrasts (see Table 13 for numerical differences and p-values) revealed significant cross-trial dimension-change RT-costs: RTs were significantly slower if the target dimension changed across trials [comparison dD vs. sDdF / positive condition: $F(1,19) = 29.981$; neutral condition: $F(1,19) = 60.128$; negative condition: $F(1,19) = 46.064$, all ps < .001]. With the analysis of only the first half of the experiment now no feature-change RT-costs for the neutral as well as for the positive condition were found: RTs did not change significantly when the target feature changed across trials [comparison sDsF vs. sDdF / positive condition: $F(1,19) = 2.028$, $p = .341$; neutral condition: $F(1,19) < 1$]. In contrast in the negative condition RTs were still significantly slowed for cross-trial feature-changes [$F(1,19) = 10.685$, $p = .008$].

	Inter-trial transition			RT-costs/-benefits$_{(change/repetition)}$		
	sDsF	sDdF	dD	$D_{(change/repetition)}$	$F_{(change/repetition)}$	p
Positive	387.3	391.4	415.2	± 23.8		< .001
					± 4.2	n.s.
Neutral	413.0	411.5	442.2	± 30.6		< .001
					± 1.5	n.s.
Negative	449.6	463.1	493.5	± 30.4		< .001
					± 13.5	= .008

Table 13: RTs (in milliseconds) separately for the four experimental conditions for the three relevant inter-trial transitions; sDsF = same dimension, same feature; sDdF = same dimension, different feature; dD = different dimension. RT-cost and -benefits associated with D = dimension and F = feature -changes and –repetitions across trials. Only the first five blocks (first half) of the experiment were analysed.

Discussion

From the present experiment it can be concluded, that observer's affect has modulated feature-based target selection. Earlier findings already proposed this for spatial attention allocation (Rowe et al., 2007).

Results were exactly as expected. Derryberry and Reed (1988) and Easterbrook (1959) proposed a spatially narrowed focus of attention for observers in negative affective states. In the present experiment it was demonstrated, that such observers processed target features rather than dimensions; RTs in feature-change inter-trial transitions were markedly increased compared to feature-repetition inter-trial transitions. Although this is an effect of feature-based processing it might be related to the assumptions of restricted spatial attentional selection, since each feature occupies a certain space in the display. The presence of cross-trial feature-based RT-costs can be interpreted in such a way, that participants in a negative mood, detected the target not on the basis of its saliency signal (feature contrast in the display), but categorised its features as a target or a non-target feature. One might argue that the distractors, a pre-requisite in order to calculate a saliency signal might not have been within the restricted spatial focus of attention, thus eliminating any feature contrast in the field. In the extreme case this hypothesis is not very likely. In addition to the feature-based RT-cost also cross-trial dimension-based RT-cost were obtained in the negative group. In other words, participants in the negative group were still able to take some advantage out of dimension-repetition inter-trial transitions. Assuming any intermediate size of the spotlight, in which not all, but the largest amount of distractors might haven been excluded from selection is not reasonable. In a parallel feature search only some/two non-target items would have added enough contrast in the according dimensional

module in order to make the target the most conspicuous item and to enable saliency-based detection, thus eliminating feature-based processing.
It is more likely, that similar to the results of Experiment 1 in which feature-and dimension-based inter-trial effects were revealed for the single item condition observer's in a negative emotional state (with a narrowed focus of attention) compared a particular stimulus against target feature templates held in working memory (feaure-based processing), but that these comparisons are dimensionally organised. The matching process might switch from one possible feature in one dimension to another feature within the same dimension (e.g., check all colour features first), before it switches to another possible feature in a different dimension (check shape features etc.), in line with Huang & Pashler (2007). This would be further support for the assumption of two weighting mechanisms operating at different processing stages (Experiment 1 and 2). One mechanism would modulate saliency signal computations, as elaborated in the DW account (Müller et al., 1995) and generate the dimension repetition benefits in the search task. For participants in a positive and neutral affective state this mechanism seemed to be sufficient in order to detect the target. But observers in a negative mood additionally to this first mechanism decided via post-selective processes whether or not the stimulus possesses the known target features in order to respond correctly. This is in accordance with Lavie (Lavie, 1995, 2005; Lavie & Tsal, 1994); the negative affect resulted in early filtering of the relevant information, but after that all processing capacity was used in order to identify the target post-selectively in order to ensure an accurate reaction. The perceptual load of the task was the same for all three emotion conditions, but it might be, that in contrast to the other emotion conditions in the negative condition participant's ensured the identity of the target after selection.

Additionally, markedly slowed RTs of observers in a negative compared to a neutral or positive emotional state were obtained. This is a well known result, especially in the clinical setting (see Christensen et al. (1997) and Veiel (1997) for reviews). Azorin, Benhaïm, Hasbroucq and Possamaï (1995) for example showed RTs of depressed patients compared to healthy controls to be slowed in a two-forced choice RT task. They additionally demonstrated this RT slow down to take place at response-related stages of the information processing. Stimulus-processing in depressed patients was unimpaired. This result reflects one of the symptoms that are accepted to be present in depressed patients, the 'psychomotor retardation' (American Psychological Association), describing the slowing down of mental processes in general.
However, from the results of this experiment, conducted with emotion induced healthy young subjects and not on depressed patients, it cannot be concluded, whether the slowed processing speed is due to slowed perceptual encoding on the pre-attentive processing stage or whether it is caused by slowed motor-related components. This will have to be investigated in further experiments.

Regarding the search performance of observers in the positive and the neutral emotional state, as expected, no significant differences in RTs and previous-trial effects were maintained. In both conditions dimension-based previous-trial effects (Found & Müller) pointed to dimensionally weighted saliency-based detection of the target.

Until now, no other study investigated emotional effects on feature-based selective attention. In this experiment it was shown, that observer's affect modulated the processing mechanisms underlying feature singleton detection, but that more research is needed in order to draw conclusions about the exact nature of this modulation.

8. Synopsis

In the field of feature-based selective attention there is a current vivid debate about the question, whether pre-attentive selection processes are modulable at all (for detailed discussions of the pre-selective position, see Müller et al. 2006, 2010; of the post-selective position, see Theeuwes et al., 2010; for a recent integrative review see Kristjánsson et al., 2010). Researchers arguing in favour for a post-selective account, as for example the Dimensional-Action model (DA; Cohen & Feintuch, 2002; Cohen & Magen, 1999; Cohen & Shoup, 1997, 2000; Feintuch & Cohen, 2002) claim early perception to be completely automatic in nature and solely driven by bottom-up stimulus properties (Maljkovic & Nakayama, 1994; Mortier et al., 2005, 2007; Theeuwes, 1991, 1992, 1994, 2004; Theeuwes et al., 2000, 2006; Schreij et al., 2008, 2010). They do not accept any kind of bottom-up or top-down modulation of the processing stage prior to attentional target selection.
On the opposite side of the debate, researchers argue for a pre-selective account, such as the Dimension Weighting (DW) model (Müller et al., 1995). In this framework pre-attentive processes are thought to be modulated by (bottom-up) dimensional weight setting adjustments, such as previous-trial (Found & Müller, 1996; Gramann et al., 2007; Müller & Krummenacher, 2006; Töllner et al., 2008) and redundant signals effects (Krummenacher et al., 2001, 2002; Töllner et al., 2010), as well as implicit (Geyer et al., 2008; Müller et al., 2009) or explicit (Müller et al., 2004, 2003; Töllner et al., 2010) top-down processes, such as the observer's goals and intentions, actively shifting attentional weight to a particular dimension. Other researcher also provided evidence for pre-attentive modulation independent of DW (Bacon & Egeth, 1994; Eimer & Kiss, 2008; Folk et al., 1992, 1994, 1998; Kiss et al., 2008; Leber & Egeth, 2006).

In the present PhD project several experiments were conducted in order to contribute to this debate, by providing further support for pre-attentive modulation and against the purely automatic view of the pre-selective processing stage. In my own experiments bottom-up (Experiment 1, 2 and 3) as well as top-down (Experiment 4) pre-attentive processing was modulated. In further experiments it was shown, that bottom-up as well as top-down components are subject to development (Experiments 5 and 6) and, that attentional selection can be modulated by observer's affect (Experiment7).

8.1 Bottom-up modulation of pre-attentive processing

Recently Mortier et al. (2005) claimed that if dimension-specific inter-trial effects originate from stages after focal-attentional selection, significant dimension repetition/change effects should arise even in tasks that do not require search for a target. They presented observers with two tasks that varied in their demands on target selection; a search versus a non-search task. In the feature search

observers discerned the presence or absence, respectively of a singleton target presented among homogenous distractors. In the non-search task the search component was eliminated by presenting the target in isolation. Participants had to discern the presented item as target (possessing target attributes) or distractor (not possessing target attributes). In both conditions they obtained previous-trial effects: participants responded faster to target dimension repetitions across consecutive trials compared to target dimension changes. Mortier et al. argued in favour of a post-selective account of dimension-based effects: "the present study showed that specific effects typically attributed to top-down guidance of search processes, also occur in conditions in which there is no search", they concluded that "these effects are the result of later processes, presumably response selection" (Mortier et al., 2005, p. 556).

Experiment 1 and 2: Inter-trial and redundant signals effects in visual search and discrimination tasks: separable pre-attentive and post-selective effects

My own research investigated whether the dimension repetition benefits in the two tasks used by Mortier et al. originated from the same, or from different – pre-attentive and, respectively, post-selective – stages of processing. Inter-trial (Experiment 1) as well as redundant signals (Experiment 2) performance was compared between a singleton feature search task (Found & Müller, 1996; Krummenacher et al., 2001, 2002), where targets were presented within an array of homogeneous distractors, and a non-search task (Mortier et al., 2005), where targets (or, on target-absent trials, distractors) were presented in isolation, thus the search component was effectively removed.

Regarding the previous-trial effects, RTs to cross-trial target (dimension and feature) changes and repetitions between multiple- and single-item(s) conditions were compared. A pre-selective locus of dimension repetition benefits would predict dimension-specific, but not feature-based previous-trial effects in the search task, because feature identity plays no role in the (pre-attentive) computations that single out the target amongst the homogeneous distractors. In contrast, in a discrimination task with a single stimulus presented, (post-selective) discrimination might be required in which target features are matched against target feature templates held in working memory. Consequently, one would expect feature-specific cross-trial effects in the discrimination task. In marked difference, on a unitary account on which all dimension-based effects originate at a post-selective stage of processing, there should be feature-specific effects in both search and non-search tasks.

With respect to the redundant signals effect, RTs to targets differing from distractors on one (colour or orientation, single targets) or on two dimensions (colour and orientation, dual [redundant] targets) between multi- and single-item conditions were compared. RTs to targets redundantly defined in two dimensions were always found to be markedly faster than RTs to targets defined in just one dimension (e.g. Feintuch & Cohen, 2002; Krummenacher et al., 2001, 2002; Mordkoff & Yantis, 1991). A pre-selective locus would predict that in the search task these RT-gains were generated in a parallel co-active process. Violations of the race-model inequality (RMI; Miller, 1982) would point to an

integration of the redundant signals prior to attention allocation, on the (pre-selective) overall-saliency map (Krummenacher et al., 2001, 2002).

By contrast, with regard to the single-item condition target attributes are assumed to be compared serially to the templates for possible targets held in working memory. Multiple simultaneous feature comparisons with target descriptions are unlikely (Huang & Pashler, 2007). Thus, not the RMI, but the Grice inequality (GI; Grice, Canham & Gwynne, 1984) should be violated ruling out parallel, but pointing to serial processing of redundant signals. Finding such a double dissociation (violation of the RMI, but not of the GI in multiple item search; violations of the GI, but not the RMI in single item non-search) together with the different patterns of previous-trial effects would provide strong evidence for different underling processes of the two tasks.

As predicted by the pre-selective locus hypothesis, results revealed no feature-specific, only dimension-based inter-trial effects and violations of the RMI, but not the GI in the search condition. This task was solved via response decisions being (largely) based on the detection of an above-threshold supra-dimensional saliency signal. Redundant signals were co-activated on the stage of cross-dimensional, overall-saliency signals computation. In the single-item condition on the other hand, feature-specific inter-trial effects, in addition to dimension-specific effects were observed. This indicates that (post-selective) feature analysis, comparing features possessed by the target with a set of target feature memory templates was involved. But comparisons within the same dimension are still given priority over comparisons involving a dimensional change in the template (Huang & Pashler, 2007). Moreover, these comparisons beyond detection are serially in nature; the GI was violated, but the RMI was not in the single item non-search task.

This pattern of effects suggests that there are two relatively independent sources of inter-trial effects in the two tasks: one located on a pre-selective processing stage, where signals are coded in a feature-unspecific, but (across dimensions) parallel co-active processing architecture; and the other one on a post-selective stage, where signals are processed in terms of precise feature information, in a serial fashion (with intra-dimensional feature switches given priority over cross-dimensional switches). Accordingly, the assumption that there is only one weighting system involved in the two types of tasks (as proposed by Mortier et al., 2005) is not tenable. The idea of multiple weighting systems operating at different levels is consistent with the DW account (Müller et al., 1995; Found & Müller, 1996), in which pre-selective weighting mechanisms can well co-exist with other short-term memory mechanisms operating at later stages in the processing hierarchy. In contrast, the single-mechanism account of Mortier et al. (2005) admits only the possibility of post-selective memory buffering, and would thus be unable to explain the existence of any inter-trial effects arising from an early perceptual processing stage.

Experiment 3: N2pc modulations by context-based redundancy gains

According to Krummenacher et al. (2001, 2002) the redundant signals effects arise at a pre-selective processing stage that follows dimension-based saliency representations. Töllner et al. (2010) recently provided support for this pre-attentive generation of the effect. RT redundancy gains were reflected in a substantial latency shortening of the perceptual N2pc component generated in redundant signals (target defined in two dimensions) relative to single signal (target defined in one dimension) displays. Furthermore, the response-related LRP components (stimulus- as well as response-locked) were not affected by the definition of the target (redundant versus single signal(s)). However, Li (2002; Koene & Zhaoping, 2007) claimed that redundancy gains would not arise at the integration stage of dimensional saliency representations (Krummenacher et al., 2001, 2002), but even earlier, at the level of neural representation of visual information in the primary visual cortex (V1). Krummenacher and Müller (unpublished manuscript) addressed this challenge by a variation of their redundant search paradigm. The target definition was held constant across trials, but the distractors changed identity from trial to trial. With respect to the number of dimensions (one or two) on which the target differed from distractors the search displays were defined singly or redundantly. Since the target defining features remained identical across trials, participants could have adopted a feature search mode (Bacon & Egeth, 1994), eliminating any modulation of search RTs, such as RT redundancy gains. This would point to signal processing in V1 (Li, 2002; Koene & Zhaoping, 2007). Results revealed in accord with Krummenacher et al.'s saliency hypothesis, RT redundancy gains of similar magnitude in the variable-target, as well as in the constant-target condition.

Own research was conducted in order to replicate and extend the findings of Krummenacher and Müller by electro-cortical measurements of event-related potentials (ERP). Participants were presented with a feature search for a singleton constantly defined by the same two features (as an example green and vertical) amongst homogeneous distractors defining the display with respect to the target in a single (colour or orientation) or redundant dimension (colour and orientation) context. Behaviourally, the results replicated Krummenacher and Müller (unpublished manuscript): RT redundancy gains as well as violations of the RMI were obtained. Furthermore, the N2pc, thought to reflect the allocation of focal attention based on perceptual stimulus attributes (Eimer, 1996; Luck & Hillyard, 1994a; Woodman & Luck, 1999) differed markedly between the conditions. The N2pc can be interpreted as the end mark of pre-attentive sensory coding. Therefore N2pc latencies index the pre-attentive processing speed, which was enhanced for redundant relative to single signals. This was shown in accelerated N2pc latencies to targets differing from distractors in two relative to one signal(s). No modulation of the stimulus- (target identification and response-selection) and the response-locked (response-execution) LRP with respect to the display identity was observed.

All in all the results support both assumptions of Krummenacher et al. (2001, 2002), that the redundant signals effect arises at i) a pre-selective processing stage that is ii) subsequent to dimension-based saliency representations. For the first assumption, that redundant signals effects arise pre-

attentively, in line with Töllner et al. (2010) the behavioural RT redundancy gains were reflected in the shorter latencies of the perceptual N2pc to redundant signals compared to single signals and additionally, no substantial modulation of the response-relevant LRPs was found. This indicates that redundant signals were integrated pre-attentively, say prior to focal attentional target selection and not on post-selective stages. The second assumption, that redundant signals effects arise subsequent to the saliency representations, was supported by ruling out the V1 hypothesis (Koene & Zhaoping, 2007; Li, 2002). Redundancy gains were found in displays, in which the to be searched target features were held constant and only the distractors changed identity. Participants were permitted to search for features (Bacon & Egeth, 1994), but they applied a singleton search mode, searching on the basis of dimensional weighted saliency representations. Consequently, the pattern of the N2pc latency modulations in the present study can be interpreted as a reflection of resource allocation (Krummenacher et al., 2001, 2002) rather than feature processing (Bacon & Egeth, 2994; Koene & Zhaoping, 2007; Li, 2002). On top of this the behavioural RT as well as the N2pc latency redundancy gains were of similar magnitude compared to the reference study of Töllner et al. (2010). This points to similar underlying processing mechanisms in both tasks of variable and constant target identity search.

8.2 Top-down modulation of pre-attentive processing

Until now, several studies were able to show top-down control of the pre-attentive processing stage. By means of a cue observers were able to set themselves for the upcoming target dimension. RTs to valid cued targets were faster and RTs to invalid cued targets were slower compared to neutral cued targets (Fecteau, 2007; Leonard and Egeth, 2008; Müller et al., 2003; Müller & Krummenacher, 2006; Töllner et al., 2010). Furthermore, inter-trial effects thought to be automatic in nature (Maljkovic and Nakayama, 1994) could be modulated by implicit (Hillstrom, 2000) and explicit (Müller et al., 2003, 2004; Fecteau, 2007; Leonard and Egeth, 2008) top-down control in experiments in which observers were pre-cued.

In order to examine endogenous versus exogenous selection, often the attentional capture paradigm is applied, in which bottom-up and top-down processes compete against each other (Theeuwes, 1991, 1992, 1994). Theeuwes (1992) found RTs to the line orientation inside a target item (compound task, Duncan, 1985) significantly slowed in displays in which besides the target another very salient distractor singleton was presented relative to displays in which the target was presented without distractor. He concluded that attention was automatically captured by the most salient item in the display and that thus RTs were slowed in the distractor present relative to the distractor absent condition. These results were replicated several times (Hickey et al., 2006; Theeuwes, 1994, 1996, 2004; Godijn & Theeuwes, 2002; Theeuwes & Van der Burg, 2008; Theeuwes et al., 2000, 2004).

However, by means of Theeuwes' (1992) paradigm Geyer et al. (2008) and Müller et al. (2009) additionally manipulated the distractor probability across experimental blocks; either 0%, 20%, 50%, 80% or 100% of the trials in the according blocks contained a distractor. Half of the observers started the experiment with a 100% distractor probability block, the other half with a 0% distractor probability block. The idea was to provide participants with different top-down sets with respect to their initial distractor experience (e.g. Leber & Egeth, 2006). Participants of the first group (100% distractor condition) were initially presented with a distractor in each trial. They were provided with a large incentive to develop a strategy to inhibit the distractor and with the ability to train this strategy from the beginning of the experiment on. But under the assumption that the incentive to suppress the distractor was only given if the cost of not suppressing the distractor is high overall, it was expected that in subsequent blocks with decreasing distractor probability (50%, 20%) distractor interference would increase again. Participants of the second group (0% distractor condition), initially being presented with no distractor trials were expected to show maximal distractor interference with the subsequent 20% distractor trials condition. Later with increasing distractor probability (50%, 80%) they were expected to develop an incentive to suppress the distractor signal. The main results were markedly decreased capture costs in experimental blocks with high compared to low distractor probability (80% versus 20%). Participants were able to actively up-modulate the weight of the target dimension or to down-modulate the weight of the distractor dimension. The dimension-based saliency signals at the level of the priority map were therefore enhanced for the target and attenuated for the distractor, so that the target was more likely to win the competition for focal attention (as the basis for a fast report of the task-relevant feature of the target).

Experiment 4: Modulated attentional capture by onset distractors

Own research was designed in order to replicate these findings under capture condition by onset distractors (OD), which are assumed to be the strongest cues to elicit bottom-up attention. In several experiments, onsets have been shown to massively capture attention (e.g. Franconeri et al., 2005; Jonides & Yantis, 1988; Yantis & Hillstrom, 1994; Yantis & Jonides, 1990; Yantis & Egeth, 1999). Recently, Schreij et al. (2008, 2010) showed that observers might be able to adopt a top-down set for colour, but that an irrelevant onset object always captured attention automatically overriding any possible top-down sets (see also Jonides and Yantis (1988) for similar results). The paradigm of Geyer et al. (2008) and Müller et al. (2009) was applied, eye movements were recorded and their results were replicated. Attentional capture by the OD depended on the percentage of OD trials within a block: the higher the percentage of ODs, the smaller the proportion of initial saccades captured by the ODs. With this paradigm it can not definitely be concluded, whether attentional capture was top-down (incentive of the observers) or bottom-up (statistical learning of distractor probability) modulated or both, though the results might be interpreted in favour for a top-down modulation. There was no significant difference in the capture rate between the groups of initial condition (0% vs. 100%); a result, predicted

by the top-down hypothesis. In the group starting with the 100% OD condition the incentive to suppress the OD would be very high in the beginning, but decrease with decreasing OD percentage, since an incentive to suppress the distractor is only given if the cost of not suppressing the distractor is high overall. For the group starting with the 0% OD condition, the incentive would be very low in the beginning due to the lack of any OD experience, but would likely rise with increasing OD probability. The top-down hypothesis would therefore predict an alignment of the capture rates of the two groups (as also found by Geyer et al, 2008). The statistical learning hypothesis on the other hand would assume an interaction between the groups Practice effects and decreasing capture probability go hand in hand for the group starting with the 0% OD condition, but not for the group starting with the 100% OD condition. The capture rate in the 0% OD condition should decrease with increasing OD probability, but the capture rate of the 100% OD condition should be low over all blocks, independent of OD probability decrease (as found by Müller et al., 2009). Since both results were obtained in three experiments using the same design, the effect of modulated attentional capture might be caused by both mechanisms. Either way, the modulation of attentional capture by onset distractors speaks against an automatic bottom-up processing on the pre-attentive stage.

The following two studies (Experiment 5, 6 and 7) differed in their underlying rationale from the studies described above as being rather exploratory in nature because they are concerned with - for the field of visual search - new topics of investigation.

8.3 Development of bottom-up and top-down attentional selection mechanisms

The aim of this research project was to investigate selective attention from a developmental point of view. The key questions were whether or not there are differences in the performance of, and the processing mechanisms underlying visual search tasks in children and adults.
Over the last few decades some research has focused on the development of selection mechanisms in visual search of children measuring preferential looking in novelty tasks (Bertin & Bhatt, 2001; Colombo et al., 1995), kick rates in mobile-conjugate reinforcement procedures (Rovee-Collier et al., 1992, 1996), pointing performance on touch screens (Gerhardstein et al., 2001, 2002), but also RTs (Donnelly et al., 2007; Trick & Enns, 1996) and eye movements (Adler & Orprecio, 2006). In all studies, with the exception of Donnelly et al. (2007), it was proposed that selection mechanisms underlying visual search are the same for infants, children and adults. This was done, although, at least in the studies that allowed direct comparisons between children and adult's performance (RT and eye movement data) always an interaction between processing speed and age was found. The younger were the observers, the slower were RTs and saccade latencies. However, this main effect was explained by ongoing motor maturation by completed myelination of sensory and motor pathways

(Adler and Orprecio, 2006; Gerhardstein et al., 2001, 2002; Trick & Enns, 1996; based on Anderson et al., 1997, Bard et al., 1990). Attentional mechanisms are not thought to be involved in the maturation process. Only Donnelly et al. (2007) pointed to a possible development of search-related cognitive factors. They tested seven-year and nine- to ten-year old children and additionally adults and found several effects that were related to the age of the observers. In a conjunction search task, search was serial and effortful in all age groups, but the younger were the observers, the higher was their search rate. Search slopes as well as search slope ratios between absent and present trials decreased with increasing age. Overall, RTs increased with increasing age in a feature as well as a feature conjunction search. Donnelly et al. (2007) provided a first piece of evidence that other (cognitive) factors, than just simple motor maturation might be involved in the development of search speed.

Experiment 5 and 6: Development of mechanisms underlying visual search; categorical and cognitive aspects

In own experiments it was aimed to investigate feature-based selection mechanisms in children compared to adults with respect to two aspects: categorical (bottom-up) and cognitive (top-down) factors. The first aspect, the development of categorical (bottom-up) factors was related to the ability of adult observers to pre-attentively unite different concrete features to superordinated constructs (i.e. to create feature categories / dimensions), which is measurable in terms of RTs (dimension-based previous-trial effects). Bruner et al. (1966) proposed that children categorise perceptually (perceptual dissimilarity affected colour pop-out) rather than conceptually (categorical dissimilarity did not affect colour pop-out) (see also Donnelly et al., 2007; Gerhardstein et al., 1999, Ross et al., 2005; Tversky, 1985). In order to test this hypothesis, a simple feature search was applied and dimension- as well as feature-based inter-trial effects were analysed. It was assumed, that if children were not able to rely on categories guiding search efficiently on the basis of weighted feature dimension salience signals (DW, Müller et al., 1995) feature-based inter-trial effects should be observed in these age groups. The second aspect, the development of cognitive (top-down) factors in visual attentional selection was related to the question, how well children compared to adults were able to solve a more complex task than a pop-out search, requiring cognitive guidance of attention. This was tested by means of a serial feature conjunction search over three different set sizes (7, 13, 19 items). The upcoming target features were additionally 100% validly symbolically pre-cued on a trial-by-trial basis. According to Donnelly et al. (2007, see also Gerhardstein et al., 2001) the set size effects (search slopes), as well as the ratios between present and absent search slopes should be more pronounced in children compared to adults in case cognitive factors would also be subject to development.

A simple feature as well as a feature conjunction search (between subject) was conducted, testing participants of different ages (six-, eight-, ten-, twelve-, 14-, 16-, 18- and 20-year olds). For both experiments a sensory-motor RT baseline (simple RT task) was additionally collected. In both the search tasks, participants had to discern target's presence and absence, respectively (two forced choice

RTs). In the baseline task, the pure appearance of any stimuli on the display, irrespective of the display identity, had to be indicated by a key press (simple RTs). The basic idea was, that according to the logic of additive factors (Donders, 1868, 1969) the RTs of the baseline task (sensory-motor RTs, no cognitive processing of the display items) can be subtracted from RTs of each search task (sensory motor plus stimulus discrimination time) in order to reveal the amount of time needed to (cognitively) identify the target in the according search task.

The results depicted RTs to the feature search, the conjunction search, the baselines (feature and conjunction baseline) as well as the calculated cognitive RTs (of the feature and the conjunction search) to increase with increasing age. Across age groups, development of the search speed was not equally distributed; a substantial acceleration of search RTs was only observed between the six- and eight-, the eight- and ten-, the ten- and twelve- and the 14- and 16-year olds. In terms of visual search, with the age of 16, search performance was matured. This RT pattern including the substantial differences between the age groups was found in both search tasks and suggests that principally the processing mechanisms underlying selective attention are subject to development.

Further, it was demonstrated that inter-trial effects for the six-year olds were feature-based in nature. If the target defining feature changed across trials, RTs increased compared to target feature repetition inter-trial transitions. No additional dimension-repetition/-change RT-benefits/-costs were observed in this age group. On the other hand, all participants aged eight and older replicated earlier results of dimension-based RT-costs and -benefits associated with changes and repetitions of the target-defining dimension. In these groups, no additional acceleration of RTs was observed if the target feature was repeated across trials (Found & Müller, 1996). It can be concluded, that participants aged eight and older were able to use categorical information, dimension-based saliency signals to sufficiently guide focal attention in order to make a correct decision about the targets presence or absence respectively. Participants aged six on the other hand performed the task on a purely feature-specific basis (no additional cross-trial dimension-repetition benefits). In other words, in line with earlier literature (Bruner et al., 1966; Donnelly et al., 2007; Frith & Frith, 1978; Gerhardstein et al., 1999; Ross et al., 2005; Tversky, 1985) participants younger than eight are not able to classify individual object features to superior dimensional concepts in order to facilitate search for a singleton feature target. Highly distinctive feature information was processed perceptually in a concrete fashion.

Finally, in both baselines of the according search tasks the sensory-motor RTs were substantially accelerated for eight- compared to six- and ten- compared to eight-year olds. This indicates that sensory and motor pathways up to age ten are still in formation. After age ten, however, no further development of these processes may be expected and the significant boost of over all search RTs must be explained by ongoing cognitive development. This assumption was strengthened by establishing a significant cognitive RT speedup between the ten- and twelve- and the 14- and 16-year olds in the feature search task. As expected, in the feature conjunction search, cognitive RTs were found to be accelerated between the three youngest age groups (six-, eight- and ten-year olds) as well. In fact, the

contingent of search-related factors on overall RT development was more pronounced in the conjunction compared to the feature search. In feature search, the decrease of search RTs for the three youngest age groups is solely explained by motor maturation. In conjunction search additionally to the sensory motor maturation, ongoing cognitive development contributes to the development of the overall search rates (in contrast to the expectations of for instance Adler and Orprecio (2006) and Trick and Enns (1998)). Furthermore, in the conjunction search the search slopes as well as the target present-absent ratio of the search slopes decreased with increasing age (e.g. Donnelly et al., 2007; Gerhardstein et al., 2001). The search slopes for target present trials of participants older than ten were not above 10 ms/item, indicating that search was parallel. It can be argued, that these participants had used the cue as a help in order to detect the target in a more parallel scanning process at least in target present trials. By contrast, the three youngest age groups were not (or less) able to use the cue information in order to boost target detection. They produced high search rates (> 10ms/item) in target present trials. In all age groups, with the exception of the six-year olds (ratio of 1.0) search slopes in target absent compared to present trials were steeper. This suggests that six-year olds, not only searched serial in target absent and present trials, but also exhaustively in both, target absent and present trials. All together, this inability (six-year olds) or reduced ability (eight- and ten-year olds) to use the supportive information of the cue might exactly be the cognitive maturation effect reflected in the cognitive RTs revealing significant differences between these three age groups in a conjunction search task. The results of both experiments are clear cut, bottom-up (from feature- to dimension-based previous-trial effects) as well as top-down (use of pre-cued information) development can be observed in the mechanisms underlying visual search for simple feature and feature conjunction targets.

8.4 Modulation of pre-attentive selection mechanisms by observer's affect

It has been proposed that attentional selection might be influenced by the current affective state of the observer (Derryberry & Tucker, 1994). It is generally accepted, that negative and positive affective states of observers lead to opposed impacts on the spatial scope of attention. Whereas the attentional focus is constricted for observers in a negative affective state (Christianson & Loftus, 1990; Derryberry & Reed, 1988; Easterbrook, 1959), it was proposed to be enhanced for observers in a positive affective state (Derryberry & Tucker, 1994; Rowe, Hirsh, & Anderson, 2007).
Until now, the influence of observer's emotions to feature-based attentional selection has never been investigated. If anything the literature present at the time focused on space- (e.g. Rowe et al., 2007) or object-based (Basso et al., 1996; Gasper & Clore, 2002) attentional selection.

Experiment 7: Modulating feature-based attentional selection by observer's affect

The narrowing or widening of the attentional scope in negative or positive affective states, respectively, was shown to modulate space-based target selection. In this experiment it was aimed to investigate, whether or not only spatial attention allocation or also feature-based attentional selection was influenced by observer's affective states. Participants were induced with either a positive, negative or neutral (control condition) emotion prior to exposure to a simple feature search task. RTs and inter-trial effects were compared across the affective groups.

In line with earlier findings results revealed reduced processing speed (RTs) for observers in the negative compared to the neutral and the positive affect condition (see Christensen, Griffiths, Mackinnon, & Jacomb, 1997; Veiel, 1997). Furthermore the negative affective state of the observers influenced target processing. The target was selected on the basis of its featural identity rather than on dimension-based saliency representations; feature- as well as dimension-specific cross-trial RT-costs and -benefits were observed in the negative emotion group. In the positive and neutral affect condition previous-trial effects were only dimensional in nature. An explanation in terms of a restricted spatial focus of attention would suggest, that the distractors in the visual field might be excluded from the spotlight (Christianson & Loftus, 1990), hindering a dimension-based saliency signal to be built up. However, this explanation seems not to be very likely, since negative participants still benefited from dimension repetitions across trials (dimension-based inter-trial effects). It might be, that similar to the results of Experiment 1 in which feature-and dimension-based inter-trial effects were revealed for the single item condition, observer's in a negative emotional state (with a narrowed focus of attention) compared a particular stimulus against target feature templates held in working memory (feature-based processing), but that these comparisons are dimensionally organised. The matching process might switch from one possible feature in one dimension to another feature within the same dimension (e.g., check all colour features first), before it switches to another possible feature in a different dimension (check shape features etc.), in line with Huang & Pashler (2007). This would be further support for the assumption of two weighting mechanisms operating at different processing stages (Experiment 1 and 2). As described above, one mechanism would modulate saliency signal computations, as elaborated in the DW (Müller et al., 1995) account, and generate the dimension repetition benefits in the search task. For participants in a positive and neutral affective state this mechanism seemed to be sufficient in order to detect the target. But observers in a negative affect additionally to this first mechanism decided via post-selective processes whether or not the stimulus possesses the known target features in order to respond correctly. However, until now, no other study investigated emotional effects on feature-based selective attention. In this experiment it was shown, that observer's affect modulated the processing mechanisms underlying feature singleton detection, but that more research is needed in order to draw conclusions about the exact nature of this modulation.

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